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An Advanced Technology Space Station for the Year 2025, Study and Concepts

M.J.Queijo, A.J.Butterfield, W.F.Cuddihy, C.B.King, and P.A.Garn

The Bionetics Corporation
Hampton, VA. 23666

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ABSTRACT

A survey has been made of potential Space Station missions that might exist in the 2020-2030 time period. Also, a brief study of the current state-of-the-art of the major subsystems was undertaken, and trends in technologies that could impact the subsystems were reviewed. The results of the survey and study were then used to arrive at a conceptual design of a Space Station for the time frame mentioned above. Factors taken into account in the conceptual design included the possible requirements for artificial gravity, synergies between subsystems, and the use of robotics. Suggestions are made relative to more in-depth studies concerning the conceptual design and alternative configurations.

ABBREVIATIONS

AC	Alternating Current
ACD	Architectural Control Document
ACS	Atmosphere Pressure and Composition Control
AR	Atmosphere Revitalization
BCU	Bridge Control Unit
BR	Bridge (Data)
CBC	Closed Brayton Cycle
CFU	Colony Forming Units
CMG	Control-moment Gyro
CPS	Control Point System
DC	Direct Current
DMS	Data Management System
DOD	Department of Defense
DOF	Degree of Freedom
E	Modulus of Elasticity
ECLSS	Environmental Control and Life Support System
EDP	Embedded Data Processor
EMU	Extravehicular Mobility Unit
EOL	End of Life
Ep	Epoxy
EPS	Electrical Power System
EVA	Extravehicular Activity
FEP	Fluorinated Ethylene Propylene
FOV	Field of View

ABBREVIATIONS (Continued)

GC/MS	Gas Chromatograph/Mass Spectrometer
GEO	Geosynchronous Equatorial Orbit
GN&C	Guidance, Navigation, and Control
Gr	Graphite
GW	Gateway (Data)
IDEAS	Integrated Design & Evaluation of Advanced Spacecraft
I/O	Input/Output
IOC	Initial Operational Capability
IPACS	Integrated Power and Control System
IR	Infrared
IRU	Inertial Reference Unit
ISA	Inertial Sensor Assembly
Isp	Specific Impulse
LEO	Low Earth Orbit
LM	Lunar Module
Mb	Megabyte
MBPS	Megabits Per Second
MDM	Multiplexer/De-multiplexer
MFR	Mobile Foot Restraint
Microrad	Microradian
Mips	Million Instructions per Second
MMC	Metal Matrix Composite
MMU	Manned Maneuvering Unit
MOD	Module

ABBREVIATIONS (Continued)

Mops	Million Operations per Second
MPD	Magnetoplasmadynamic
MPAC	Multi-Purpose Application Console
Mrad	Milliradian
MRMS	Mobile Remote Manipulator System
MSU	Mass Storage Unit
NASA	National Aeronautics and Space Administration
NIU	Network Interface Unit
NM	Nautical Miles
NOS	Network Operating System
OAO	Orbiting Astronomical Observatory
OMV	Orbital Maneuvering Vehicle
ORC	Organic Rankine Cycle
ORU	Orbital Replaceable Unit
OS	Operating System
OTV	Orbital Transfer Vehicle
PDCA	Power Distribution Control Assembly
PLSS	Portable Life Support System
PROP	Propulsion
PV	Photovoltaic
Q	Heat Flux
RCA	Radio Corporation of America
RCS	Reaction Control System
RF	Radio Frequency

ABBREVIATIONS (Concluded)

RFC	Regenerative Fuel Cell
SAB	Spacecraft Analysis Branch
SAT	Satellite
SD	Solar Dynamic
SDP	Standard Data Processor
SOTA	State-of-the-Art
SPAR	Space Power Advanced Reactor
S/S	Space Station
SSE	Subsystem Sensor and Effector
T_1	High Temperature
T_2	Low Temperature
TDAS	Tracking and Data Acquisition Satellite
TDRSS	Tracking and Data Relay Satellite System
TGS	Time Generation System
THC	Temperature and Humidity Control (Module)
VF	View Factor
WAO	Wet Air Oxidation
ρ	Density
ε	Emissivity

AN ADVANCED TECHNOLOGY SPACE STATION FOR THE YEAR 2025, STUDY AND CONCEPTS

M. J. Queijo, A. J. Butterfield, W. F. Cuddihy,
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The Bionetics Corporation

SUMMARY

The Bionetics Corporation was tasked by the NASA Langley Spacecraft Analysis Branch to perform a study, consisting of four parts, relating to an advanced technology Space Station for the time period around 2025. The four parts were:

1. Examine the capabilities (functions) that a Space Station might be required to perform.
2. Review the Space Station major subsystems to determine state-of-the-art and the predicted trends in subsystem technology.
3. Synthesize candidate advanced subsystem configurations.
4. Create an integrated Space Station configuration using advanced subsystem configurations.

The first part of the study was a review of literature concerned with proposed and suggested future space missions. The review resulted in a list of seventeen possible functions which could be performed on or by a manned Space Station in support of the missions:

1. A permanent observatory to look down upon the earth and out into the universe

2. An orbiting science, medical, materials, and new technologies laboratory
3. A service and repair facility for payloads, spacecraft, and platforms
4. An assembly facility where large structures or spacecraft components are manufactured and/or assembled and checked out
5. A transportation node where payloads and vehicles are collected, stationed, processed, and launched and where fuel is manufactured
6. A safe habitat for space crews
7. A communications and/or relay station for manned or unmanned spacecraft
8. An adaptation area (in variable "g") in preparation for long space flights
9. A storage node for food, fuel, spare parts, etc.
10. A variable "g" research facility
11. A commercial manufacturing facility (drugs, crystals, etc.)
12. An energy collection and relay station
13. A diagnostic, medical, and convalescent facility
14. A tourism attraction
15. A horticultural research and food growth facility
16. A technology demonstration facility
17. A control center for manned and unmanned spacecraft

Note that the above requirements are based on civilian use of the Space Station. Military applications could well add other requirements.

The list of capability requirements are not, by any means, listed in order of priority. The priority could be determined by the station capability or by the national needs at that time. For example, commercial needs for microgravity processing could be a priority, or the use of the station as a transportation node to colonize the Moon or Mars might be of the highest priority.

The second part of the study involved a survey of the state-of-the-art of spacecraft subsystems and the predicted technology trends in those subsystems. The major subsystems have been identified in several reports as the following:

1. Electrical Power
2. Guidance, Navigation, and Control
3. Structures and Mechanisms
4. On-board Propulsion
5. Thermal Control
6. Environmental Control and Life Support
7. Extravehicular Activity
8. Communications and Tracking
9. Data Management

The Initial Operational Capability Space Station uses state-of-the-art subsystems. In some cases, these are essentially the existing subsystems in the Shuttle Orbiter or those felt to be advanced to the point where they are proposed for the Initial Operational Capability Space Station.

Trends in subsystem technology were examined by literature search and by use of the NASA Technology Model.

A conceptual 2025 Advanced Technology Space Station was outlined, based on the trends in subsystem study and on a few guidelines devised as a result of the work statement, the literature search, and group discussions. These guidelines were:

1. Make use of synergy between subsystems.
2. Provide a semi-closed life-support system assuming adequate on-board power availability and relatively low-cost resupply capability.
3. Provide artificial gravity for normal crew activities as well as a zero gravity capability for experiments. For this preliminary study, a lunar "g" was selected for living conditions.
4. Provide shirtsleeve working environment and passageways to reduce extravehicular activity.

Finally, a list of suggested topics for additional research for the suggested or alternate Space Station configurations is presented.

A BRIEF STUDY LEADING TO A CONCEPTUAL DESIGN OF AN ADVANCED TECHNOLOGY SPACE STATION FOR ABOUT THE YEAR 2025

1.0 INTRODUCTION

Space travel and exploration of the solar system has long been a dream of mankind. Rocket research by Robert Goddard and many others, and analytical studies by engineers and mathematicians such as Herman Oberth and Konstantin Tsiolkovsky, began to open the possibility of manned space flight. Finally in 1958 man took his first steps into space when Russian Cosmonaut Yuri Gagarin was launched into low Earth orbit. This feat was duplicated by American Astronaut John Glenn, and mankind was on its way to the exploration of space. Since that time, progress has been fairly rapid, and the United States has had a series of successful manned projects such as Mercury, Gemini, Apollo, Spacelab, and Shuttle flights. Each project had a specific purpose and, at the same time, provided logical steps to increase the capability of advancing the exploration of space and utilizing the space environment.

A current major space project involves the development of a manned Space Station in low Earth orbit and operational within this century, a goal which has been widely discussed for many years (**Reference 1**). The Space Station will provide an initial operational capability (IOC) for Earth observation, scientific studies, and commercialization. It is anticipated that the Space Station capability and size will increase as plans evolve and technology advances, that the Space Station will assume additional functions, and that subsystems will be changed or replaced to take advantage of new technology.

At some point in time, a totally new advanced Space Station may evolve because of new or additional requirements or subsystem changes. Some of the possible requirements, or functions, of such an Advanced Technology Space Station and associated technology advances will be reviewed in later sections of this report. A time frame around the year 2025 is selected to permit new technology development and to reach well defined capabilities required of a future Space Station. The purpose of the present study is to evaluate some of the possible characteristics of such an Advanced Technology Space Station.

It should be noted that because of the limited number of manhours devoted to the very broad study areas, the results will necessarily be conceptual. However, results of this study led to a suggested configuration and to subsystem choices and identified areas for more detailed analyses.

2.0 ADVANCED TECHNOLOGY SPACE STATION CAPABILITY REQUIREMENTS

In order to determine the capability that might be required of an Advanced Technology Space Station, it is necessary to consider what missions it might perform or support. A reasonable place to start is a review of proposed or envisioned missions that might require the use of a Space Station. A current list of proposed space missions is given in **Reference 2.** The missions fall into seven categories, as shown in **Table 2.0-1.** Supplementary information on the missions is given in **Reference 3.** An additional source to examine for future space missions is "The Report of the National Commission on Space" (**Reference 4**). The Commission was appointed by the President of the United States and was charged by Congress to formulate a bold agenda to carry America's civilian space enterprise into the twenty-first century. The goals proposed by the Commission were "To lead the exploration and development of the space frontier, advancing science, technology, and enterprise, and building institutions and systems that make accessible vast new resources and support human settlements beyond Earth orbit, from the highlands of the Moon to the plains of Mars" (**Reference 4**). The recommendations of the Commission on space imply some additional mission categories such as:

1. Human colonization of the Moon and of Mars
2. Mining the planets and moons of some of the planets
3. Space tourism

Another source for possible space missions is the National Space Transportation and Support Study (**Reference 5**).

When all the above categories of missions are considered and projected to about the 2020-2030 time frame, it is possible to generate a list of

TABLE 2.0-1 STATISTICS FROM NASA MISSION MODEL (REFERENCE 2)

Mission Category	No. of Missions in Funding or Development Status A	P	C	O	Total Missions
Solar System Exploration	3	4	11	5	23
Astrophysics	7	11	7	15	40
Earth Sciences	7	6	8	0	21
Life Sciences	4	0	0	1	5
Communications	4	0	3	1	8
Space Transportation	9	4	2	3	18
Utilization of Space Environment	4	1	0	3	8

KEY

A = Approved, funded and on-going
B = Planned, start within 5 years
C = Candidate, start within 10 years
O = Opportunity, start after 10 years

functions that could be performed on or by a manned Space Station. A possible scenario to consider is a large Space Station in Earth's orbit, possibly accompanied by tethered or free-orbiting platforms, while other space probes or manned missions are being launched. The following list suggests some roles that a Space Station might serve:

1. A permanent observatory to look down upon the earth and out into the universe
2. An orbiting science, medical, materials, and new technologies laboratory
3. A service and repair facility for payloads, spacecraft, and platforms
4. An assembly facility where large structures or spacecraft components are manufactured and/or assembled and checked out
5. A transportation node where payloads and vehicles are collected, stationed, processed, and launched and where fuel is manufactured
6. A safe habitat for space crews
7. A communications and/or relay station for manned or unmanned spacecraft
8. An adaptation area (in variable "g") in preparation for long space flights
9. A storage node for food, fuel, spare parts, etc.
10. A variable "g" research facility
11. A commercial manufacturing facility (drugs, crystals, etc.)
12. An energy collection and relay station
13. A diagnostic, medical, and convalescent facility

14. A tourism attraction

15. A horticultural research and food growth facility

16. A technology demonstration facility

17. A control center for manned and unmanned spacecraft

Note that the above requirements are based on civilian use of the Space Station. Military applications could well add other requirements.

Note that the list of capability requirements are not, by any means, listed in order of priority. The priority could be determined by the station capability or by national needs at that time. For example, commercial needs for microgravity processing could be a priority, or the use of the station as a transportation node to colonize the Moon or Mars might be of the highest priority.

3.0 SPACE STATION SUBSYSTEMS, TECHNOLOGY ASSESSMENTS, AND SYNTHESIS

The Advanced Technology Space Station and the IOC Space Station are comprised of subsystems which require tailoring and integration into an operational unit. The steps to configure an Advanced Technology Space Station first identified the principal subsystems and then reviewed the IOC configuration together with the assessments and projections of technologies to provide the basis for synthesizing the Advanced Technology Space Station.

3.1 Major Subsystems for Review

The major subsystems identified in the early Space Station studies (**Reference 6**) have continued to appear in the later studies. The subsystems are:

1. Electrical Power
2. Guidance, Navigation, and Control
3. Structures and Mechanisms
4. On-board Propulsion
5. Thermal Control
6. Environmental Control and Life Support
7. Extravehicular Activity
8. Communications and Tracking
9. Data Management

3.2 Reviews and Assessments

The reviews and assessments of the technologies began with the descriptions for the Dual Keel IOC Space Station (**Reference 6**) as indicated in **Figure 3.2-1** as the point of departure for assessing the status and

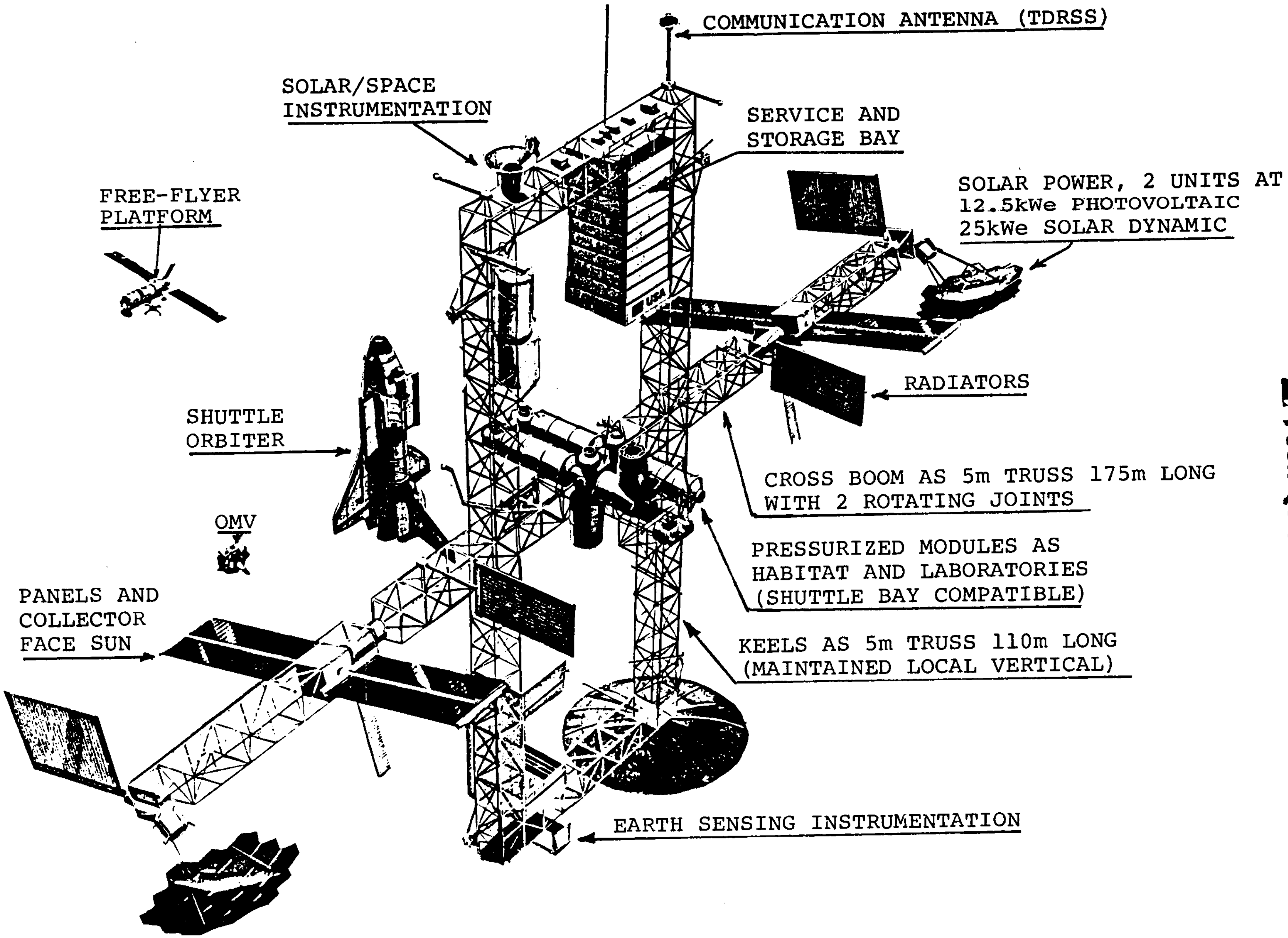


Figure 3.2-1 Baseline Configuration Dual-Keel Space Station, Principal Features

projections for technology accomplishments which could be incorporated into the Advanced Technology Space Station. In the assessments for the individual subsystems which follow, the IOC configuration and its relation to the current status of that technology are the first items addressed. These subsystem definitions plus the forecasts for technology accomplishments of **Reference 3** became the general base for synthesizing the subsystems incorporated into the Advanced Technology Space Station.

3.3 Advanced Subsystems Synthesis and Synergies

The descriptions for the Advanced Technology Space Station resulted from assessment and iterations of configurations. In each of the iterations, the concept of synergistic interactions between subsystems received particular attention. The final configuration, shown as **Figure 3.3-1** and described more completely in Section 6, represents considerations for accomplishing all seventeen of the functions identified within one Space Station, while at the same time achieving significant synergies between subsystems. In that context, the discussions of individual subsystems begin with the IOC and lead to the Advanced Technology Concepts with potential synergies identified. The synergies appear summarized as Section 5, and the description of the proposed configuration for the Advanced Technology Space Station appears as Section 6.

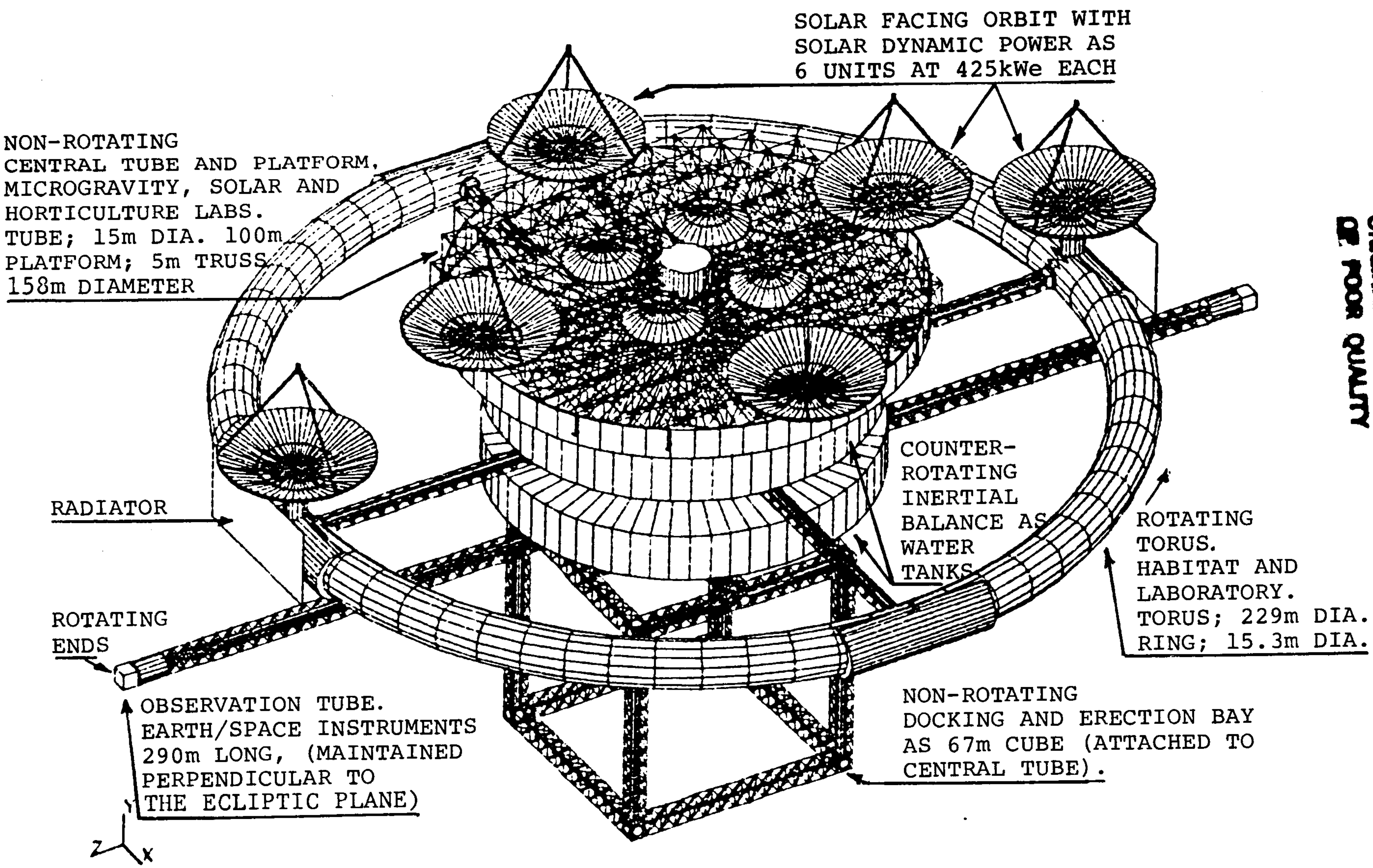


Figure 3.3-1 Advanced Technology Space Station Concept, Principal Features

4.0 SUBSYSTEM STATE-OF-THE-ART, TECHNOLOGY TRENDS, AND CANDIDATE ADVANCED SUBSYSTEMS

The Space Station design has already undergone several changes, and the design will continue to evolve as it proceeds through the development steps. In this study, the dual-keel configuration (**Figure 3.2-1**) is used as a starting point because it is the one on which much study already has been done in defining the overall station requirements and the various subsystems. The subsystems themselves are described in **References 6 and 7**. The following sections are brief summaries of the current subsystems, technology trends, and candidate advanced subsystems.

4.1 Electrical Power Subsystem

4.1.1 State-of-the-Art Electrical Power Subsystem

The design of the Electrical Power Subsystem (EPS) is documented in the Architectural Control Document (**Reference 7**). Copies of this document, which are updated as revisions are received from the Johnson Space Center, are maintained at the Langley Space Station Office (Building 1212) and at The Bionetics Corporation (20 Research Drive, Hampton, Virginia).

The 75 kW power output IOC EPS, as given in the June 24, 1986, update of the EPS, is a hybrid generation subsystem consisting of two solar dynamic (SD) and two photovoltaic (PV) modules. There is a single SD generation system in each SD module and two solar array wings in each PV module. The SD supplies two thirds of the power, and the PV supplies one third of the power (50 kW and 25 kW respectively). Energy storage for the SD system is by phase-change salts, and for the PV system NiH_2 batteries are specified.

Power source converters provide 20 kHz, single phase, 400 volts AC to Power Distribution Control Assemblies (PDCA's), which in turn supply the Space Station loads. **Figure 4.1.1-1** shows the simplified features of the EPS architecture (**Reference** 7).

The IOC PV systems will use SOTA Lockheed planar, flexible substrate, deployable and retractable silicon arrays. The SD system has not been chosen, but the current choices being considered are limited to a closed Brayton Cycle (CBC) or an Organic Rankine Cycle (ORC).

There are ten external load areas which are supplied by a modified dual-ring bus system. The four IOC modules will each be supplied through two penetrations utilizing transformers to provide isolation for a single point ground. For life critical loads, the EPS is capable of providing two-fault tolerant power. **Table 4.1.1-1** summarizes the major features of the current EPS.

The IOC EPS is loaded with control computers and microprocessors for automatic operation, fault detection and switching, collector pointing, status reporting, and interfacing with other subsystems. The Data Management Subsystem (DMS) has a major interface with the EPS for reporting EPS status and for interfacing the requirements of other subsystems back to the EPS. The overall coordination of power management is performed by the Power Management Controller.

4.1.2 EPS Technological Trends

Space Station growth may take the form of larger and larger structures with ever-increasing power demands or moderate growth and multiple special application individual stations, each with its own unique power

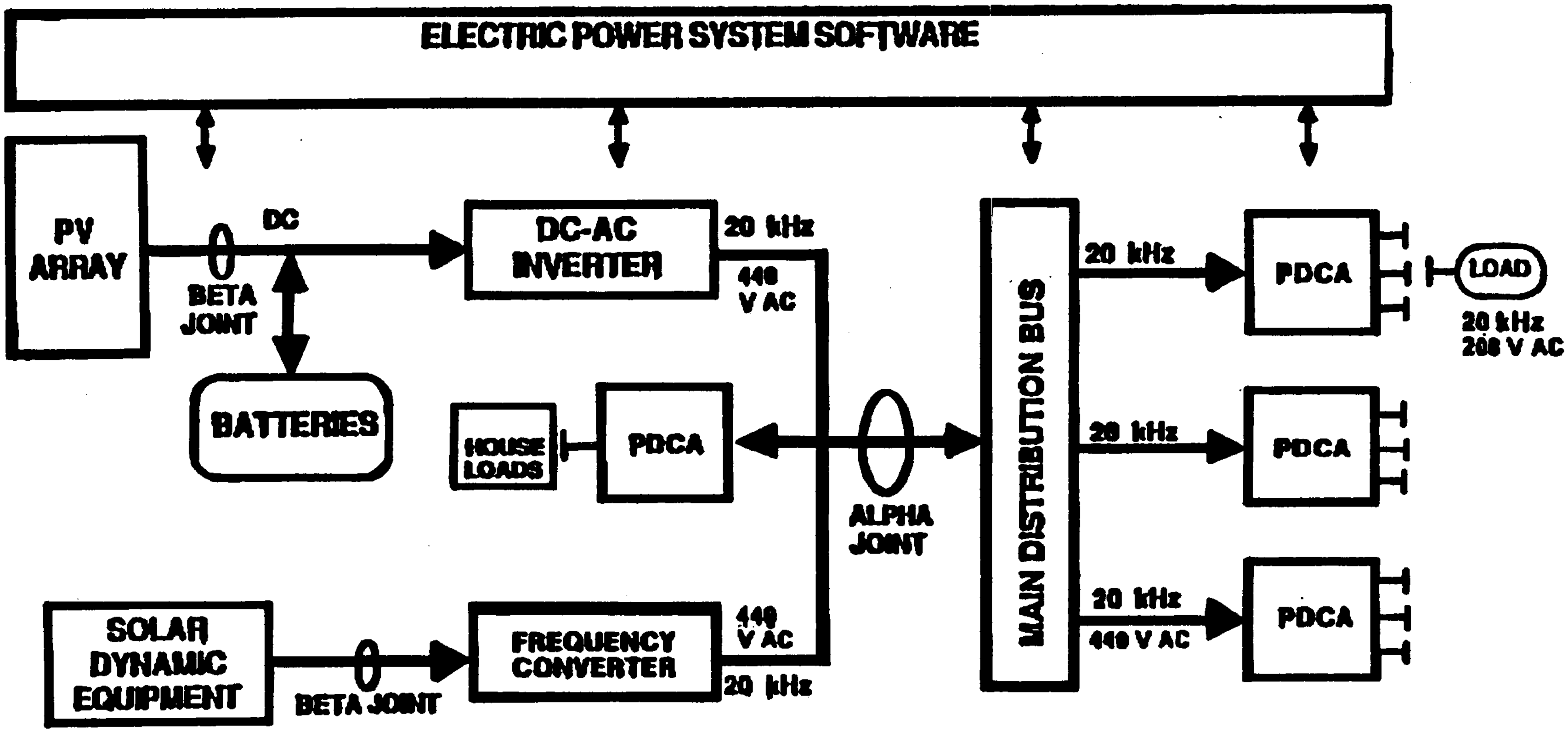


Figure 4.1.1-1 Simplified Features of the EPS Architecture (Reference 7)

TABLE 4.1.1-1 CURRENT SPACE STATION ELECTRIC POWER SYSTEM*

Two PV Modules	Two SD Modules
o Lockheed silicon flex. deploy./retract. arrays o 12.5 kWe/module o 25 kWe total o Energy storage, NiH_2 batteries	o Type of SD units not specified o Limited to ORC or Brayton o 25 kWe/module o 50 kWe total o Energy storage, phase-change salts
o Two failure tolerant power to life essential loads o Modified dual-ring distribution bus o Single point ground o Main distribution bus 20 kHz, 440 volts AC, single phase o Power distribution and control assemblies (PDCA's) 20 kHz, 208 volts AC, single phase at modules and attached payloads o Hierarchy of control computers and microprocessors throughout EPS o Monitoring system commonality with DMS	

*6/24/86 Version, Architecture Control Document (Reference 7) requirements. Examples of individual stations with diverse power requirements would be: low-power--geosynchronous communication and monitoring units; medium-power--LEO earth science and payload servicing; high-power--manufacturing, interplanetary staging stations, or Lunar Orbiting Space Stations to support lunar surface activities. Some activities such as in-situ fuel manufacturing would be especially demanding in power requirements.

For future power subsystems, important considerations include the impact of overall efficiency on size and weight and the need for high reliability and graceful failure modes. Nuclear power systems impose an additional requirement for assuring non-contamination from a launch failure or re-entry and for obtaining the necessary approvals for launch of radioactive material.

The overall efficiency of a power system is influenced not only by source conversion efficiencies, but also by energy storage requirements and on-board power processing requirements. For example, the original IOC reference 75 kW PV system had a collection area of 1785 m^2 to produce 75 kWe continuous power for 37 percent earth shadow operation. At 1.35 kW/m^2 solar flux, the overall conversion efficiency was less than 5 percent.

If a solar input EPS with an overall efficiency of 5 percent is improved to 50 percent, the collective area is decreased by a factor of ten. If it were possible to continue improvements and approach 100 percent efficiency, the additional area reduction would only be by a factor of two. This final area reduction is 5 percent of the original area. Thus, other factors such as ease of maintenance and commonality with other systems might be of greater importance than further efficiency improvement.

For any heat engine working between two temperature limits, the maximum efficiency available is that for a Carnot cycle (**References 8 and 9**).

$$\text{Efficiency} = \frac{T_1 - T_2}{T_1} = \frac{\Delta T}{T_1} = 1 - \frac{T_2}{T_1} \; *$$

The low temperature operational point of most terrestrial heat machines is tied to the ambient temperature. For space applications, cold space can provide low temperature radiator operation--for a given ΔT, the lower the high temperature operational point, the greater the efficiency and the easier the maintenance requirements. The radiator area needed, however, increases as the inverse fourth power of temperature. Improvements in the design of low temperature radiators using new concepts such as liquid droplet radiators will provide a bonus to heat engines for future Space Station applications.

A power system will require a prime source of energy, an energy storage method, and a means of transforming energy to a form suitable for a given task. The prime energy sources currently being considered for Space Station include solar, nuclear radioisotope or reactor, and stored chemical or mechanical energy lofted into orbit. Recent advances in laser design and in particle physics would indicate that fusion energy might be available in the time period of this study (**Reference 10**).

To first order, the energy source and energy conversion methods may be considered separately. That is, a Stirling heat engine may be powered by a solar source or by a nuclear source such as a fixed bed reactor, a space

*Footnote: (T_1 = high temperature, T_2 = low temperature. These are equivalent to T_H and T_C in References 8 and 9. Letter subscripts are avoided here because terms such as "cold" and "collector" temperature and "radiator" and "receiver" temperature can be confused.)

power advanced reactor, or a radioisotope heater. However, advantages may accrue by synergistic relations between components, such as is indicated in **Reference 11**, wherein a proposed 8.7 MW power system uses the same working fluid for a Brayton heat engine and a nuclear fixed bed reactor.

The energy conversion methods can be subdivided into direct conversion to electrical energy and heat engines to provide rotating or reciprocating mechanical energy for conversion to electrical energy. For purposes of this study, a few of the direct and heat engine methods of energy conversion will be listed. Direct conversion methods include solar cells (silicon, GaAs, and multi-gap), thermomagnetic, thermoelectric, and thermionic schemes as well as electrodynamic using tethers. In the electrodynamic tether case, energy is removed from the orbital velocity and restored by the propulsion system. Heat engines include Rankine, Brayton, and Stirling. Perhaps new approaches such as the use of shape memory alloy metal heat engines may become practical for space power systems.

It is likely that high power output, on-board systems will be superseded by the use of remote units transmitting power to a manned Space Station or that multiple specialized Space Stations will reduce the need for large power systems in conjunction with highly populated Stations. High energy applications using relayed power might use tethered distribution lines or laser or microwave power transmission (**Reference 12**).

Very efficient use of waste heat and synergism between subsystems may reduce per-unit operational power requirements. That is, in the evolution of the Space Station, on-board power requirements would peak due to operational and generation efficiencies exceeding growth needs. Another factor that would reduce central power generation requirements would be the increased use of self-contained modular packages which would provide local power generation.

A 2025 Advanced Technology Space Station may use power sources or conversion methods very different from those covered here. The ability to deliver mass and volume to orbit may be less critical than at present, and on-orbit production and refurbishment could make design lifetime less critical than employing modular change-out and fail-safe redundancy philosophies. The projections, however, of a few values as found in the literature may be useful.

The NASA Technology Model (**Reference 2**) contains useful projections for some of the EPS components out to the year 2000. The technology forecast table for electrical power is reproduced in **Table 4.1.2-1.**

For solar cell powered systems, the theoretical limits of efficiency are already being approached and it will require a breakthrough in multi-band material or direct conversion methods to significantly exceed 25 percent efficiency, which in turn fixes the power per unit area in the range of 300 watts per square meter for unshaded operation without storage or distribution allowances. **Reference 13** describes a 75 kW GaAs concentrator system with a 61 watt per square meter output.

For a comparison of solar and nuclear sources, the projections of **Reference 13** are reproduced in **Figures 4.1.2-1 through 4.1.2-3.** The power per unit mass for a 300 kW solar Stirling system is about 25 watts per kilogram. **Figure 4.1.2-4,** from **Reference 13**, includes a comparison of masses when propulsion requirements are included. **Reference 11** describes an 8.7 MW nuclear Brayton system utilizing a liquid droplet radiator with a 537 watt per kilogram design. Assumptions about shielding requirements, system

TABLE 4.1.2-1 POWER SYSTEMS TECHNOLOGY FORECASTS (REFERENCE 2)

Figure of Merit	1985	1990	1995	2000
Solar Arrays				
Specific Power (W/kg)	60	120	180	250
Power Level (kW)	25	40	250	--
Design Lifetime (yr)	10	12	15	15
Cell Efficiency (%)	17.5	20	24	24
Specific Cost ($/W)	300	180	100	90
Specific Power (W/m^2)	170	190	240	240
Secondary Cells				
Energy Density (W-hr/kg)				
Ni/Cd, LEO/GEO	10/20	12/25	15/30	20/35
Ni/H_2, LEO/GEO	30/35	32/40	32/42	32/45
HEDRB, GEO	*	92	100	110
Design Lifetime (yr)				
Ni/Cd, LEO/GEO	7/12	8/13.5	9/14.5	-/15
Ni/H_2, LEO/GEO	4/7	7/11	9/13	-/14
HEDRB, GEO	*	5	6	10
Primary Cells				
Energy Density (W-hr/kg)				
$Li/SOCl_2$	250	325	--	--
Ag/Zn	150	180	--	--
Design Life (yr)				
$Li/SOCl_2$	8	10	--	--
Ag/Zn	2	2	--	--
Radioisotope Thermoelectric Generators				
Efficiency (%)	8.5	10.5	--	--
Specific Power (W/kg)	4.5	6.5	8	--
Design Life (yr)	6	7.5	8.5	10
Nuclear Reactors				
Power Level (kW)	*	*	100	100
Specific Power (W/kg)	10	20	30	50
Power Conversion Efficiency (%)	6	9	12	--
Fuel Cells				
Specific Power (W/kg)	110	115	122	130
Power Level (kW)	50	100	175	--
Specific Cost ($/W)	25	20	15	10
Power Control Systems				
Specific Power Handling (W/kg)	72	80	85	85

*Technology not available.

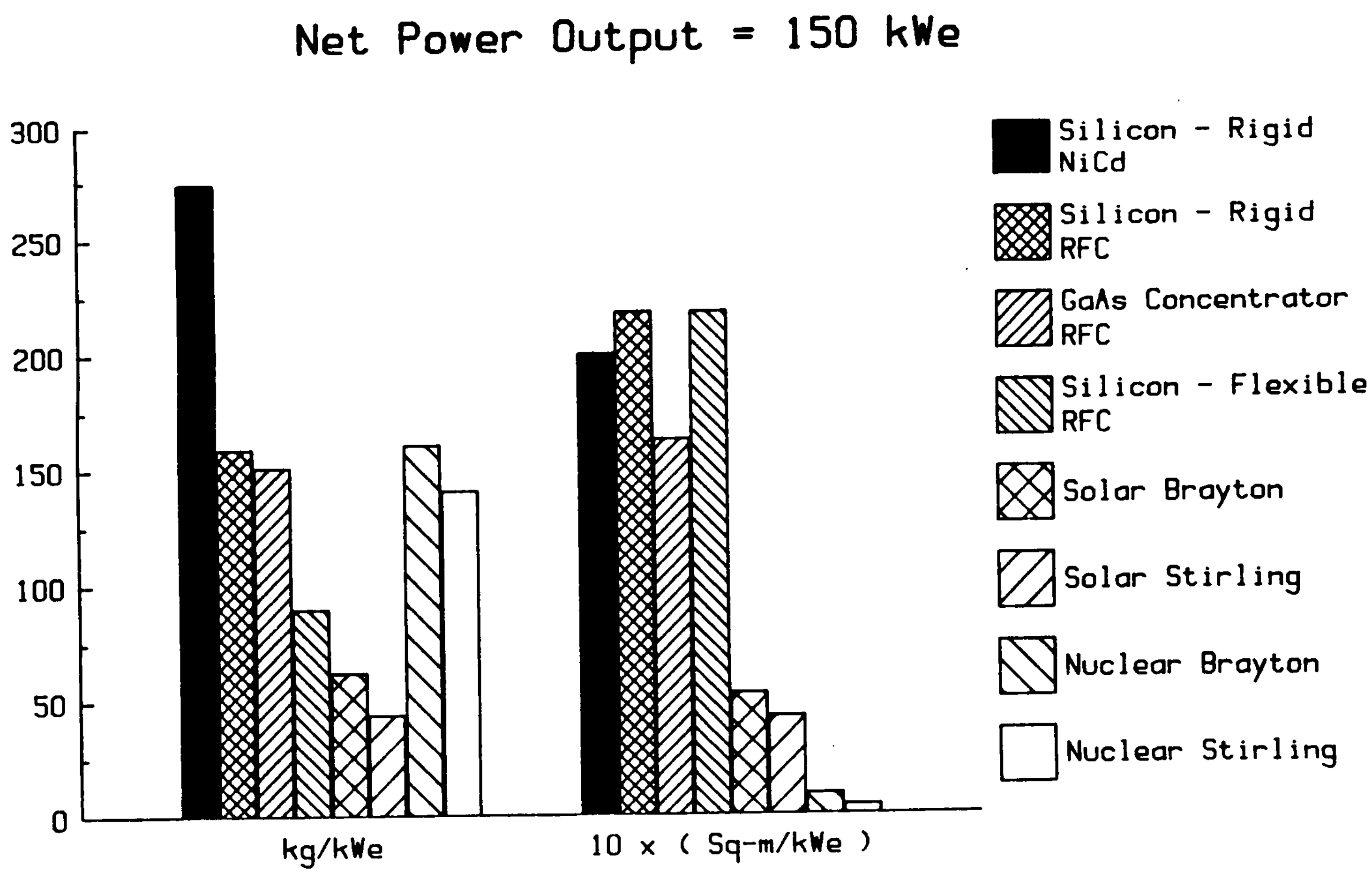


Figure 4.1.2-1 Specific Mass and Area of Several Space Station Power Systems (Reference 13)

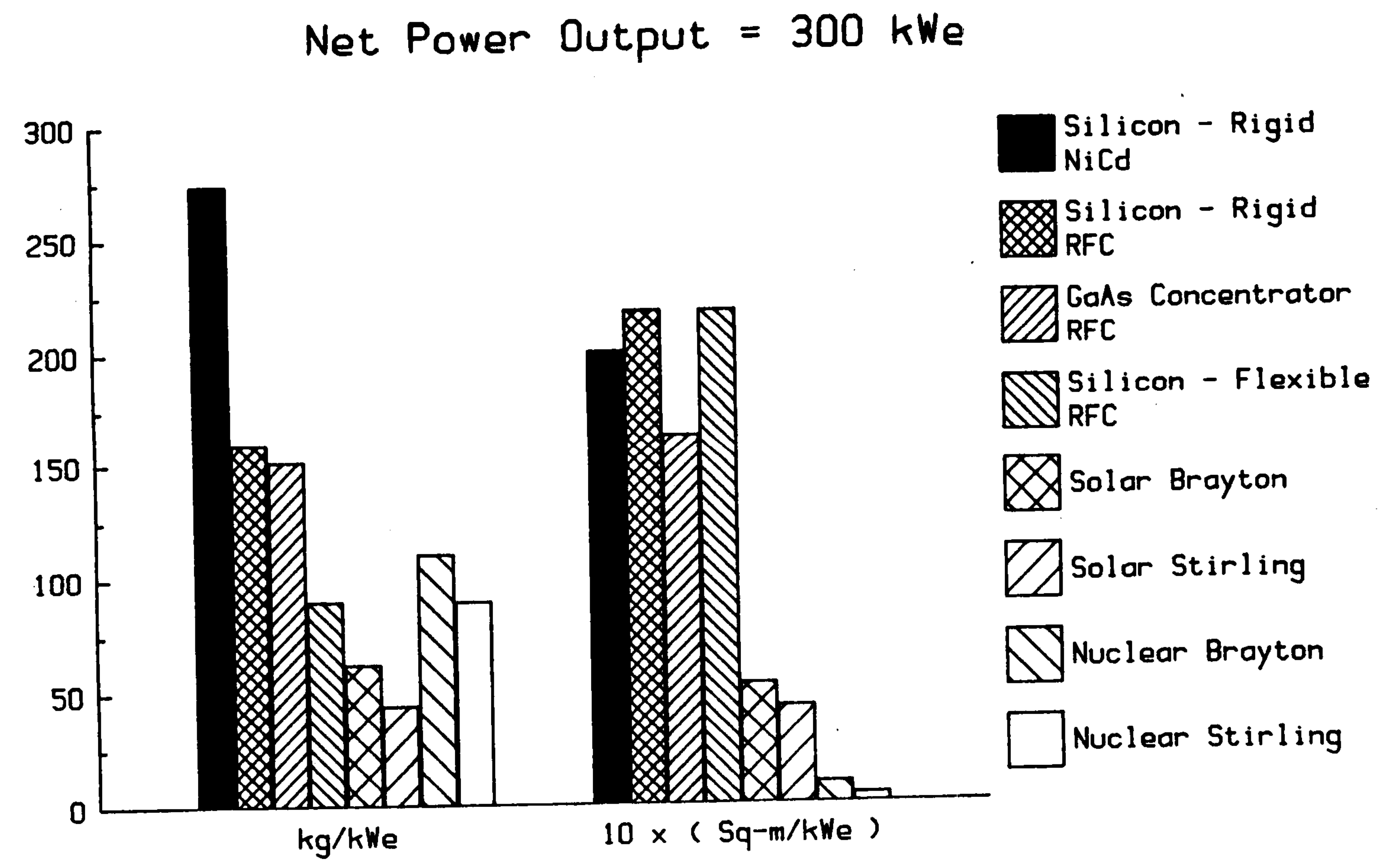


Figure 4.1.2-2 Specific Mass and Area of Several Space Station Power Systems (Reference 13)

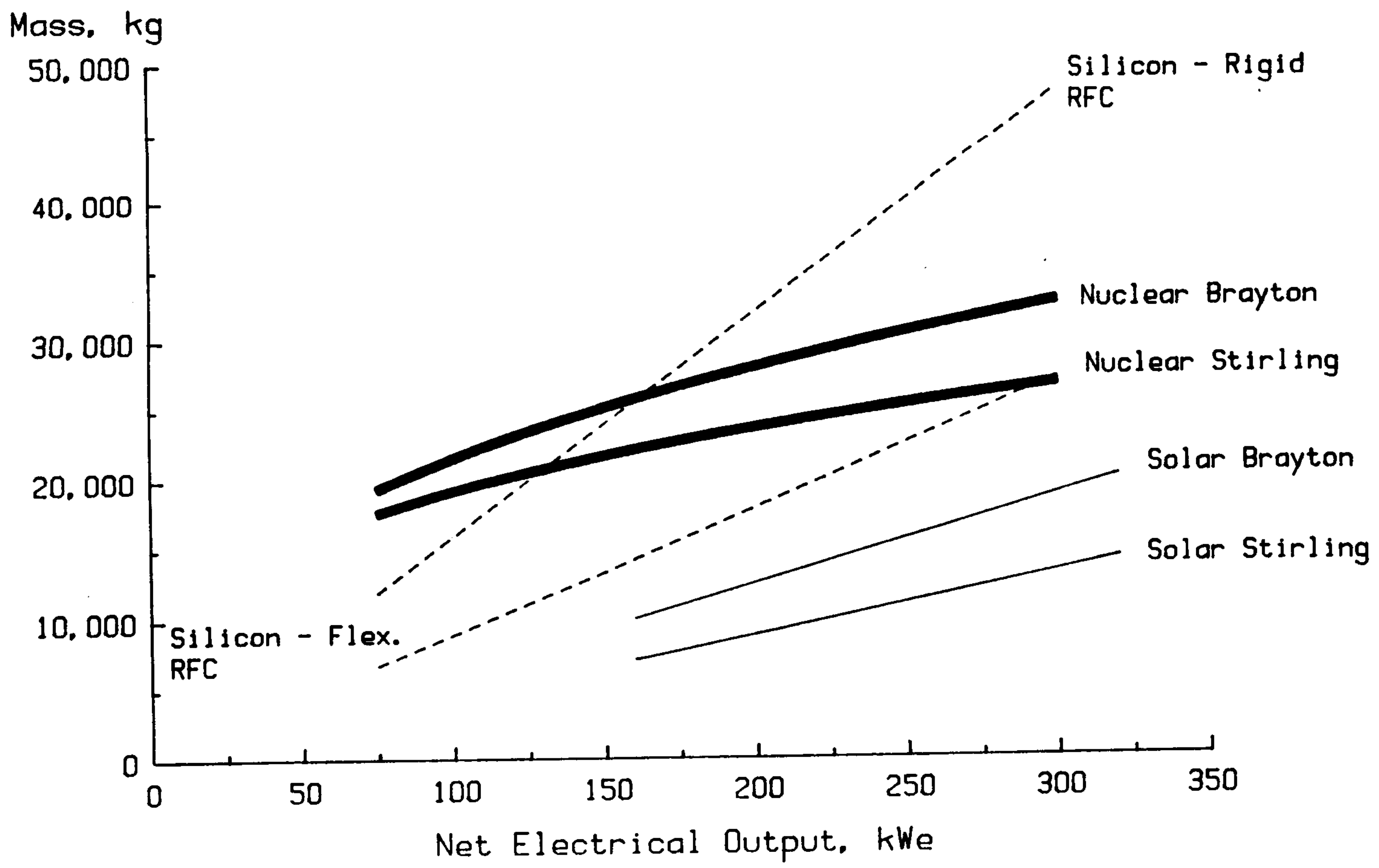
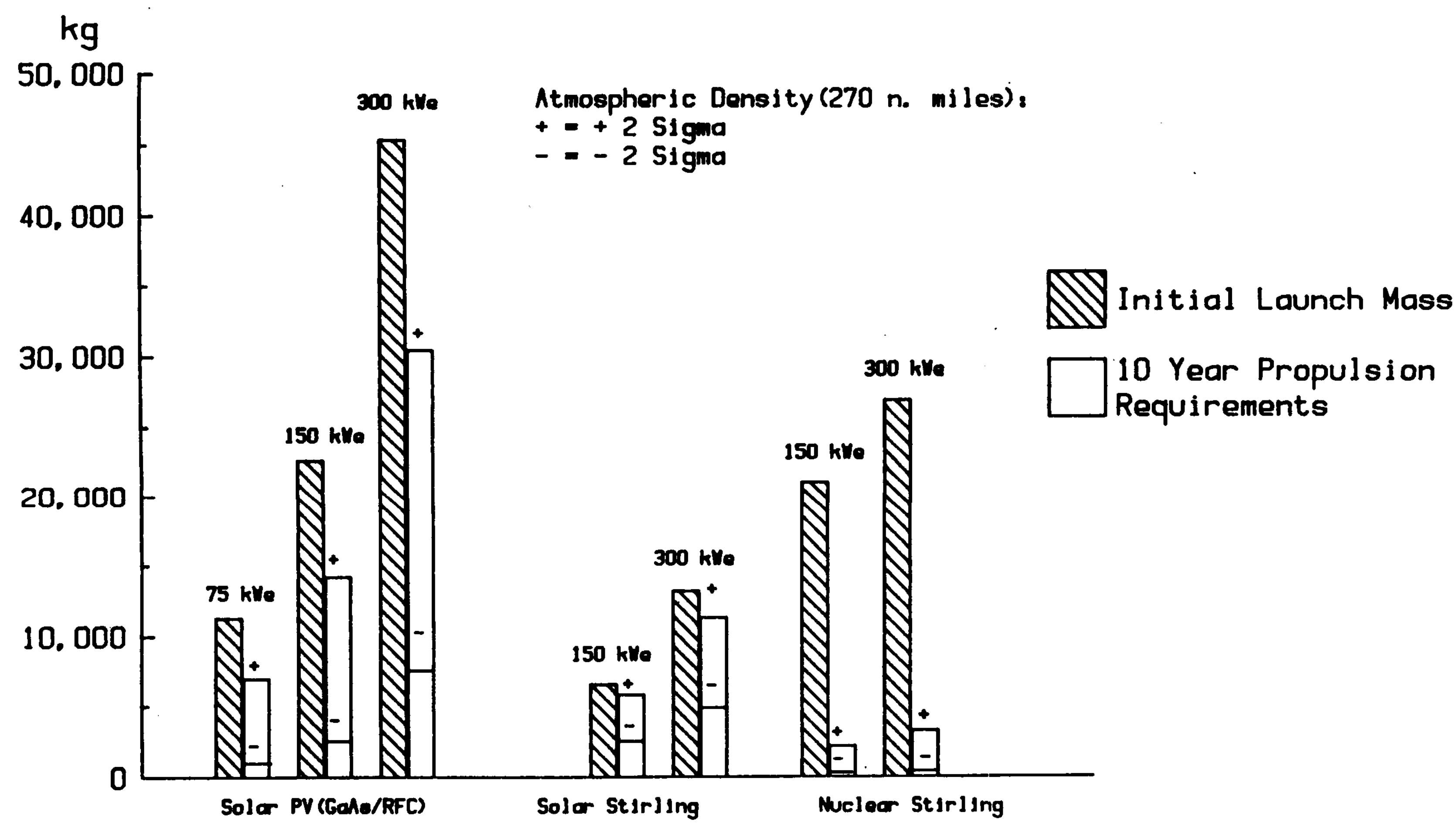


Figure 4.1.2-3 Total System Mass for Potential Space Station Power Systems (Reference 13)



Isp = 425 sec
10 m moment arm

Figure 4.1.2-4 Initial Launch Mass and 10-Year Propulsion Requirements for Several Space Station Power Systems (Reference 13)

efficiencies, and energy storage requirements will greatly influence the projections in this section.

4.1.3 Candidate Advanced Electrical Power Subsystem

As indicated in the previous section, high power generation and high power applications may be isolated from the populated Space Station. However, for this point design, an on-board system is chosen to support all seventeen Space Station functions listed in Section 2.0. This choice, which requires large collector and radiator areas as well as Sun inertial orientation in conjunction with the rotational requirements for artificial gravity, will serve to identify subsystem requirements for a large EPS.

For the point design, we assume a power subsystem of 2.5 MWe output. The manufacturing and fuel generation requirements are the major energy users. **Table 4.1.3-1** lists the power allocations which include a 36 percent margin. The number of modules and spares to provide this output would vary with operational requirements; for this case, we have chosen six units. Two units supply power to the artificial gravity rotating section, and four units supply power to the stationary section. These units would be self-monitoring and self-repairing by automatic switching to redundant parts. Adequate intelligence would be built in to signal when redundant parts were at a predetermined level and to alert to failure trends or generic failure modes. The system would alert when manned or robotic maintenance was required by either on-board Space Station action or return to Earth for refurbishment.

The energy conversion method is a generic heat machine operating at 80 percent of Carnot efficiency. The actual type (Stirling, shaped memory

TABLE 4.1.3-1 PERSONNEL AND POWER REQUIREMENTS

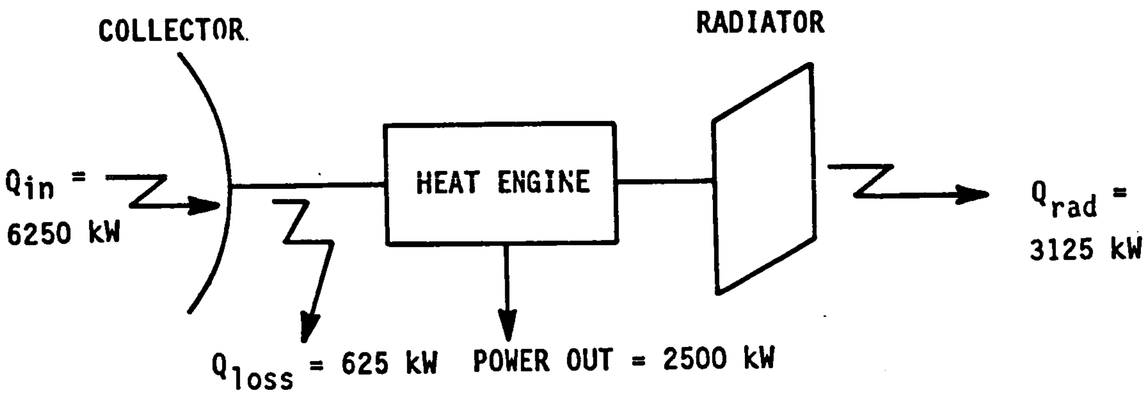
Function	Personnel	Power
Operations	12	200 kW
Science	10	100 kW
Transients	14	20 kW
Medical	6	20 kW
Manufacturing & Fuel	12	1500 kW
Contingency	6	660 kW
Total	60	2500 kW

alloy metal, new approach, etc.) is not important in determining operating limits. The 80 percent of Carnot is an arbitrary selection that sets the heat engine ΔT.

The collector area is determined by the overall efficiency, the solar flux, and the time spent in Earth shadow. The radiator area is selected to be the same as the collector area, which is reasonable from drag and structural considerations. The radiator temperature is determined by its emittance, view factor, and the power radiated to cold space. The inlet temperature to the heat engine is determined by how close the heat engine works to the maximum efficiency of a Carnot cycle. These factors are illustrated in **Figure 4.1.3-1**, which provides calculations for the point design. The calculations are normalized and plotted as a function of overall efficiency in **Figure 4.1.3-2.** The diminishing returns in reducing the size of collector and radiator and the higher temperatures that must be designed to as a function of efficiency increase are illustrated in this Figure. Operating temperatures are shown on the radiation plot of **Figure 4.1.3-3.** A factor that is not included in these calculations but which will definitely limit the maximum efficiency obtainable is reradiation of energy from the receiver as T_1 increases. A design factor that controls this reradiation is receiver aperture area, which in turn is controlled by collector mirror surface smoothness and shape and by collector pointing accuracy.

Another point should be noted relevant to **Figure 4.1.3-2.** For a heat engine operating at 80 percent Carnot efficiency and the overall efficiency selected, the collector area and power output are directly related independent of the power level chosen. For example, a 25 kW power module at

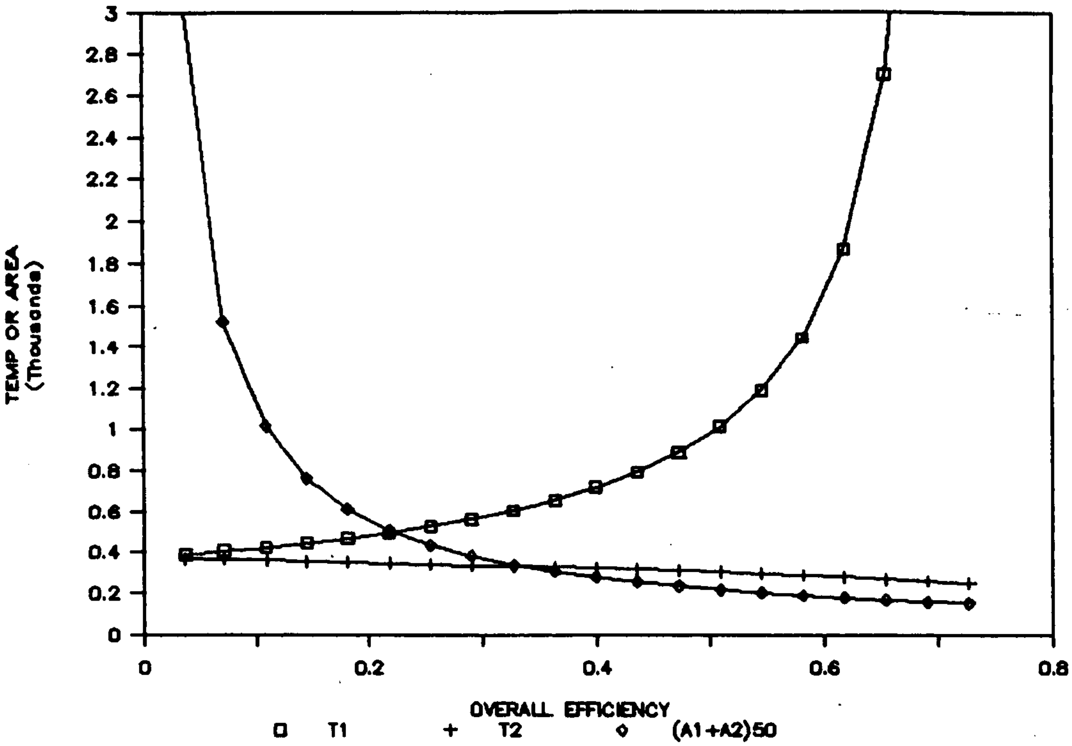
CRITERIA - . POWER OUTPUT 2500 kWe . OVERALL EFFICIENCY 40% . LOSSES BEFORE HEAT ENGINE 10% . HEAT ENGINE 80% OF CARNOT . RADIATOR: e = 0.85, vf = 0.9



- SOLAR INPUT = 1.35 kW/m^2 x 2/3 DAYLITE = 0.9 kW/m^2 AVERAGE
- COLLECTOR INPUT = Qin = 2500/0.40 = 6250 kW
- COLLECTOR AREA = 6250/0.9 - 6944 m^2 (DIAMETER = 94 m)
- RADIATOR AREA = COLLECTOR AREA = A_1
- EFFECTIVE RADIATOR AREA = A_1 x e x vf = 6944 x 0.85 x 0.9 = 5312 M^2 = A'_r
- RADIATED POWER PER m^2 = 3125/5312 = 0.59 kW/m^2

  RADIATED POWER IS ALSO = $5.6 \times 10^{-11}\ T_2^4$ kW/m^2
- RADIATOR TEMP = T_2 = 320 K = 47° C
- HEAT ENGINE EFFICIENCY = 2500/(6250-625) = 44.4%
- EFFICIENCY MAXIMUM = EFFICIENCY H.E./CARNOT FRACTION = 44.4%/80% = 55.5%
- INLET TEMPERATURE = T_1 = T_2/(1-EFFICIENCY MAXIMUM) = 720° K = 447° C

Figure 4.1.3-1 Point Design Calculations



Qwork(kW)=	1.00	Qheateng=	Qw/EFFhe	Ar'=Ar*vf*e	
EFFICIENCY	(VARIABLE)	Qradiate=	Qhe-Qw	Qr/M^2=5.6*10^-11*T2^4	
Qinput=	Qhe+Qloss	AREAinput=Qin/(1.35*2/3)			
Qloss=	10% Qhe	AREArad=	AREAinput	T1=T2/(1-EFFmax)	

Figure 4.1.3-2 Temperature and Area Versus Efficiency

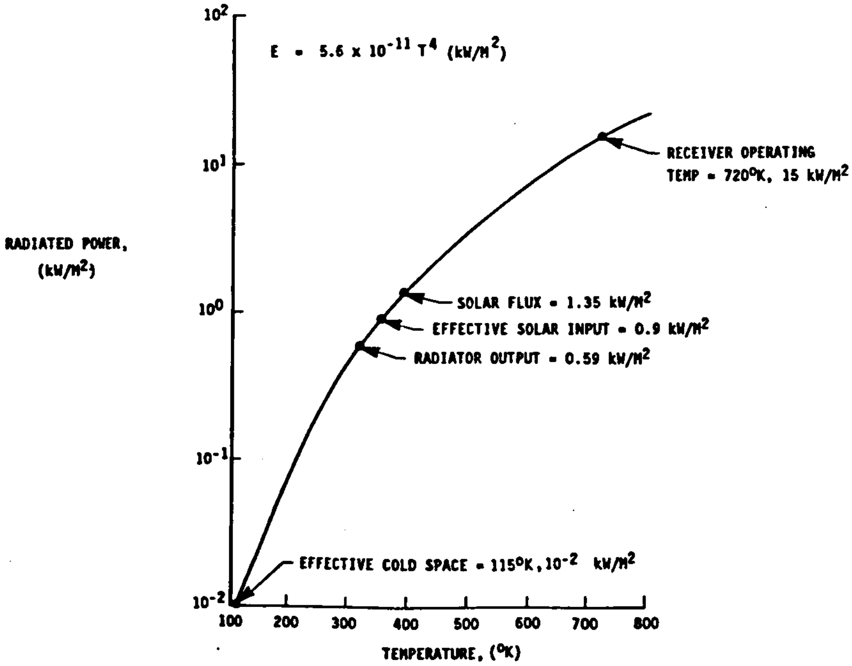


Figure 4.1.3-3 Blackbody Radiation

40 percent overall efficiency would operate at $T_1 = 720^\circ$ K and $T_2 = 320^\circ$ K with a collector area of 69.5 m^2, whereas a 2.5 MWe system would operate between the same temperatures with a collector area of 6,950 m^2. In actual practice, there is an economy of scale, usually providing higher efficiencies as the power level increases (**Reference 14**).

Two methods of energy storage are employed. Phase-change materials (not necessarily salts) are used as a buffer to regulate input to output energy and as a direct source of high level heat for the thermal control system. Water is electrolyzed, and hydrogen is stored in absorption materials. The oxygen is stored cryogenically. In addition, energy stored in angular momentum associated with the control subsystem and the artificial gravity subsystem can be tapped.

4.2 Guidance, Navigation, and Control (GN&C) Subsystem

This is a major Space Station subsystem and is critical to many functions, including orbit maintenance, solar pointing, attitude control, experiment stability, and proximity operation.

4.2.1 State-of-the-Art

The baseline control system (**Figure 4.2.1-1**) is a centralized system of attitude and rate sensors, and control-moment gyros control effectors that provide station stabilization. The navigation system uses inertial sensor assemblies: rate gyros and accelerometers to provide attitude, attitude rate, position, and velocity; star trackers to update attitudes; and the Global Positioning System satellites to update position and velocity.

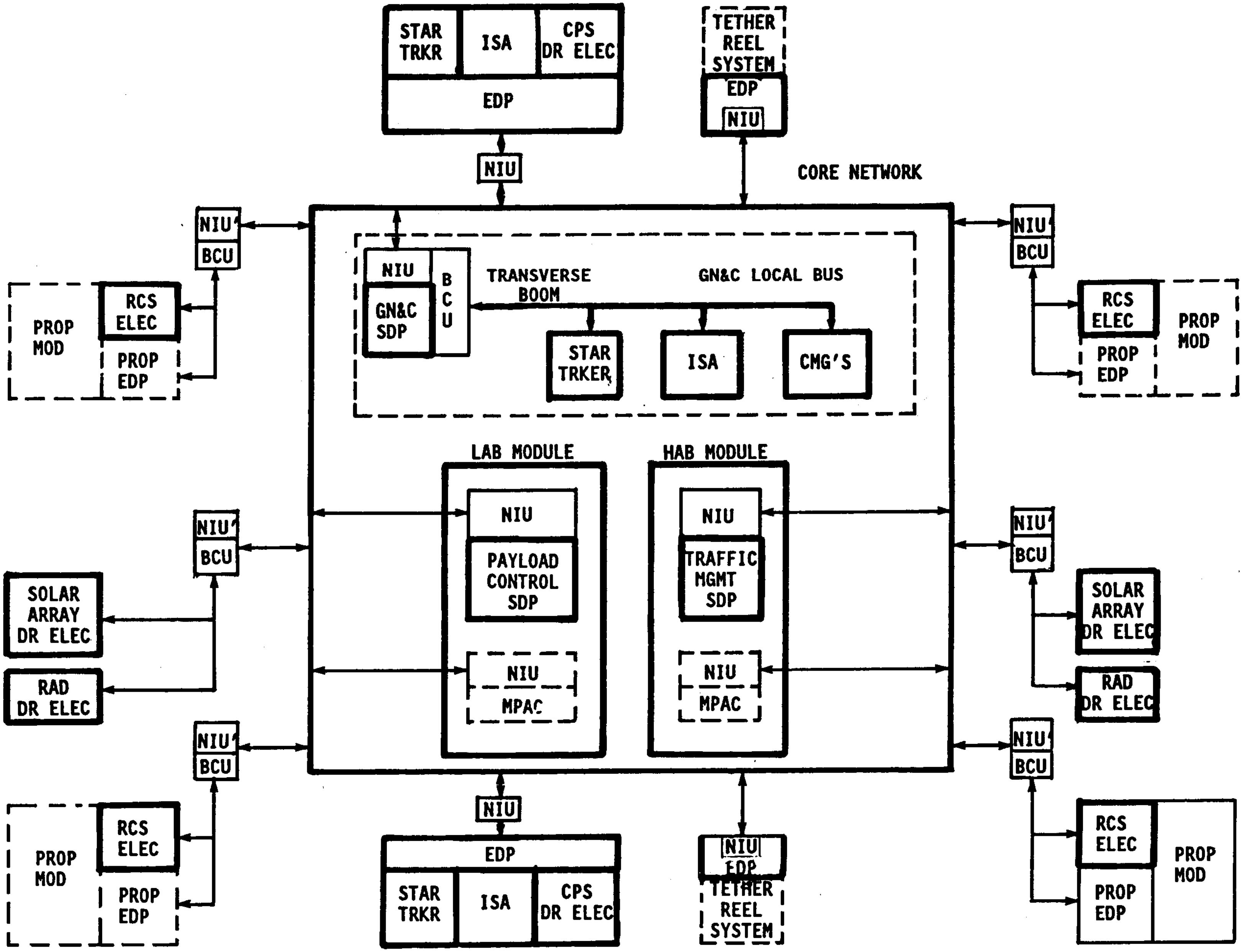


Figure 4.2.1-1 Space Station GN&C Architecture (Reference 7)

Primary attitude control will be through the use of control-moment gyros. Supplementary control moments by use of magnetic torquers are indicated in **Reference 6**, but not in **Reference 7**. The reaction control system will be used to perform any required translation maneuvers. In addition, the reaction control system will be used to back up the control-moment gyros and the magnetic torquers, if necessary. Reaction control will be attained by placing thrusters in positions to produce torques around and thrusts along three orthogonal body axes. The reaction control system will be used to reboost the Space Station when required and may be used to avoid collision with orbiting objects. All the control systems will be able to operate individually or simultaneously.

The equipment list for the GN&C subsystem includes a pair of star tracker triads, two 3-axis inertial sensor assemblies, six control-moment gyros, and numerous components that provide electronic support to the GN&C subsystem.

The GN&C subsystem has management responsibility for traffic control and proximity operations of station traffic operating within the Space Station's area of influence in order to insure that operational procedures meet safety and mission constraints. The GN&C subsystem also will have the capability of monitoring and controlling vehicles whose trajectories may, at some time, cause them to enter the area of influence. The Station's area of influence is, by definition, a 30° cone about the positive and negative velocity vectors of the Station out to 2,000 kilometers and the entirety of a sphere of radius 8 kilometers around the Station.

The Space Station GN&C equipment list is presented in **Table 4.2.1-1** along with weight and volume parameters.

TABLE 4.2.1-1 SPACE STATION GN&C EQUIPMENT LIST (REFERENCE 6)

Unit Description	Dimensions Per Unit (In.)	No. Units	Vol. Unit (Cu.Ft.)	Vol. Total (Cu.Ft.)	Weight Per Unit (Lbs.)	Weight Total (Lbs.)
Actuators						
CMG Assembly	42 Sphere	6	22.45	134.70	420.00	2520.00
Magnetic Bar	2.25 Dia.x98	6	0.23	1.35	109.00	654.00
Total Actuators				136.05		3174.00
Sensors						
Star Tracker Triad	13x13x12	2	1.17	2.35	20.00	40.00
Hexad Strapdown	12x12x12	1	1.00	1.00	50.00	50.00
Spares for above	12x12x12	1	1.00	1.00	50.00	50.00
Total Sensors				4.35		140.00
Electronic Support						
Magnetic Torquers	9x9x9	6	0.56	3.38	20.00	120.00
RCS Cont System	12x18x8	3	1.00	3.00	35.00	105.00
G&C Processors	7.5x10.5x15	3	0.68	2.05	20.00	60.00
NAV/Traffic Proc	7.5x10.5x15	3	0.68	2.05	20.00	60.00
Interface Devices	7.5x10.5x15	18	0.68	12.30	5.00	90.00
Solar Array Elec.	8x9x6	6	0.25	1.50	12.00	72.00
Spares for above	8x9x6	3	0.25	0.75	12.00	36.00
Radiator Elec.	8x9x6	2	0.25	0.50	12.00	24.00
Spares for above	8x9x6	1	0.25	0.25	12.00	12.00
Payload Elec.	2x5x6	2	0.04	0.08	3.00	6.00
Total Electronics				25.86		585.00
Grand Totals				166.26		3899.00

4.2.2 Technology Trends

Increased performance in GN&C systems is driven by the apparent need for large space structures, large optical assemblies and antennas, and high precision orbit determination. The orbit determination requirements (navigation) could be handled by on-board systems or could be handled by existing highly developed ground tracking facilities, computer facilities, and associated algorithms for data processing. Proximity navigation, associated with collision avoidance, probably could be aided by on-board radar tracking units.

Predicted technology trends for the primary components of the GN&C hardware are given in **Table 4.2.2-1** (from **Reference 2**). One emerging technology that appears quite attractive is the use of laser or fiber optics gyros for measuring angular rates. Fiber optic gyros are predicted to be about 15 times as accurate as spun mass gyros by the year 2,000. **Reference 15** contains detailed discussions of inertial technology trends. It is interesting to note that of the three types of gyros (spun mass, laser, and fiber optics) only the fiber optics gyro is predicted to meet the requirements for the Saturn Orbiter/Titan Probe (needed by 1989) and that of the Large Deployable Reflector (needed by 1993). The IRU drift accuracy requirements are 0.03 mrad/hour and 0.01 mrad/hour, respectively (**Reference 2**).

Other advanced concepts for attitude control include the dual momentum vector control concept (**Reference 16**) and the Integrated Power and Attitude Control System, IPACS (**Reference 17**). The latter integrates the angular momentum control and energy storage function. **Reference 17** indicates that recent technology advances in composite rotors, magnetic bearings, and power

TABLE 4.2.2-1 NAVIGATION, GUIDANCE, AND CONTROL TECHNOLOGY FORECASTS (REFERENCE 2)

Figure of Merit	1985	1990	1995	2000
Guidance and Navigation				
Position Accuracy (m)	5	2.5	1	--
Geoid Residual (cm)	150	--	10	--
Pointing, Vibration, and Figure Control				
Viscoelastic Materials Damping Coefficient (%)	1	2.5	4	--
Pointing Accuracy (mrad)				
Earth-Pointing Systems	1.5×10^{-2}	1×10^{-2}	7×10^{-3}	3×10^{-3}
Inertial Systems	5×10^{-3}	4×10^{-3}	3×10^{-3}	2.5×10^{-3}
Stellar Systems	3×10^{-4}	1.5×10^{-4}	1.2×10^{-4}	1×10^{-4}
Pointing Stability (microrad)	3×10^{-2}	1.2×10^{-2}	7×10^{-3}	3×10^{-3}
Pointing Stability Rate (microrad/sec)	5	2	1	0.7
Maneuvering Settling Time (sec)	0.6	0.25	0.2	--
Inertial Rate Unit Drift (mrad/hr)				
Spun Mass Gyros	0.2	0.15	0.12	0.12
Laser Gyros	0.07	0.05	0.05	0.05
Fiber Optics Gyros	*	0.01	0.008	0.007
Active Earth Sensor Accuracy (mrad)				
Low Earth Orbit	5	3	2.5	2
Geosynchronous Orbit	1.2	--	--	1
Star Tracker Accuracy (microrad)				
8° FOV Charge Transfer Devices	10	7.5	5	3
1° FOV Charge Transfer Devices	1	0.75	0.5	0.3
Momentum Wheel Angular Momentum (N-m-s)				
Reaction Wheels, Medium Speed	100	200	600	2000
Reaction Wheels, High-Speed	250	600	2000	3000
Control Moment Gyros, 1-DOF	3,000	5,000	9,000	11,000
Control Moment Gyros, 2-DOF	9,000	12,000	20,000	--
State Variable Estimation (no. states)	25	50	250	1,000

*Technology not available.

control electronics have triggered new optimism regarding the feasibility and merits of such a system.

4.2.3 Candidate Advanced Subsystem

An advanced candidate GN&C subsystem would contain all of the elements of the current state-of-the-art subsystem (**Table 4.2.1-1**) but would use the latest technology available. Selection of actual hardware components will depend to a large extent on such factors as reliability, durability, ease of maintenance and/or repair, availability, cost, size, and weight. Other factors to be considered are redundancy, fault tolerance, and failure or malfunction detection. Some of these factors are related to development of control algorithms for the various functions.

4.3 Structures and Mechanisms Subsystems

The Space Station (IOC) design and structural configuration will be limited by the development of advanced materials, their manufacturing concepts, and the volume/weight lift capabilities of the Space Shuttle to low Earth orbit.

The assembly of the IOC Space Station may be accomplished using astronauts performing EVA. An alternate assembly concept for the Space Station is under development and could employ a free flying tele-robot with a man-in-the-loop.

4.3.1 State-of-the-Art

The planned Space Station (IOC) will be assembled using as a foundation a dual-keel truss structure to which pressurized modules and the mechanisms of the operational Space Station will be attached. The construction will consist of 5-cm-diameter elements joined at spherical nodes to fabricate a truss structure consisting of 5-m bays.

One preliminary design of a tubular element for erectable assembly in space consists of a wall construction of 0.15-cm-thickness composite formed of axially collimated carbon fiber reinforced epoxy resin. The composite is clad on both the inside and outside diameters with 0.015-cm-thickness aluminum alloy. Threaded aluminum alloy sleeves are adhesively bonded into the tube ends, one end with a right-hand thread, the opposite end with a left-hand thread to effect a turnbuckle concept. The strut attachment fittings are assembled with the tubular element struts and adjusted by rotation to achieve precise strut length.

Spherical aluminum alloy nodes are numerically machined and threaded at twenty-six locations to receive node attachment fittings. The attachment fittings are prelaunch assembled to the nodes by cap screws (**Figure 4.3.1-1**).

The attachment of each strut end to its corresponding node attachment fitting is accomplished in space by astronaut manual assembly of an erectable strut joint. A sidelatching of the joint occurs when the joint is hand clasped transversely to the strut's axis. The astronaut secures the joint by rotating a cam cover 45° to apply joint preload (**Figure 4.3.1-2**).

One concept of assembly of the Space Station dual keel will utilize a Mobile Remote Manipulator System (MRMS). The MRMS is a platform which can move one bay at a time being supported on the truss structure by MRMS guide pins located at the structure's nodes.

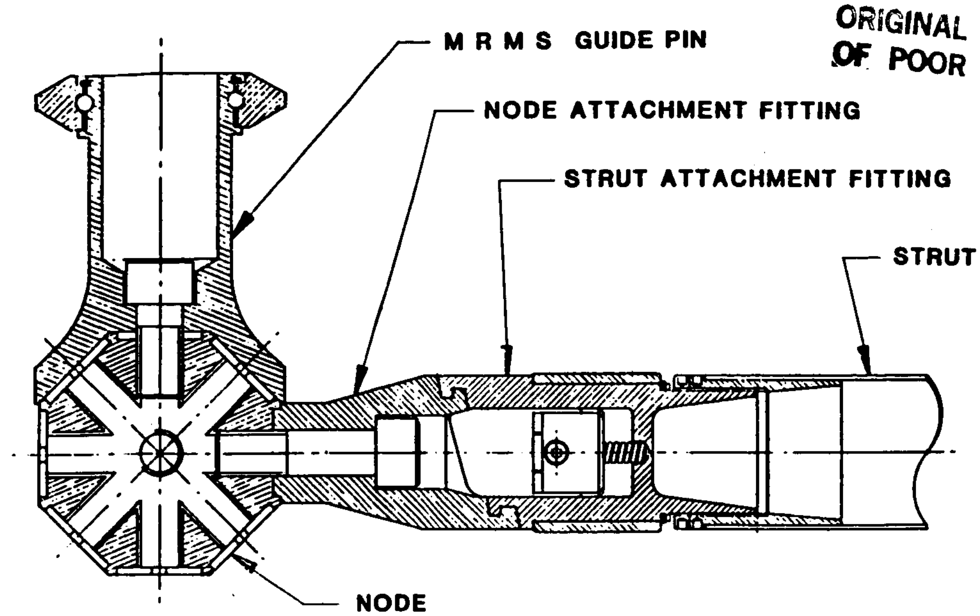


Figure 4.3.1-1 Erectable Strut Attachment Method (LaRC Concepts Under Development)

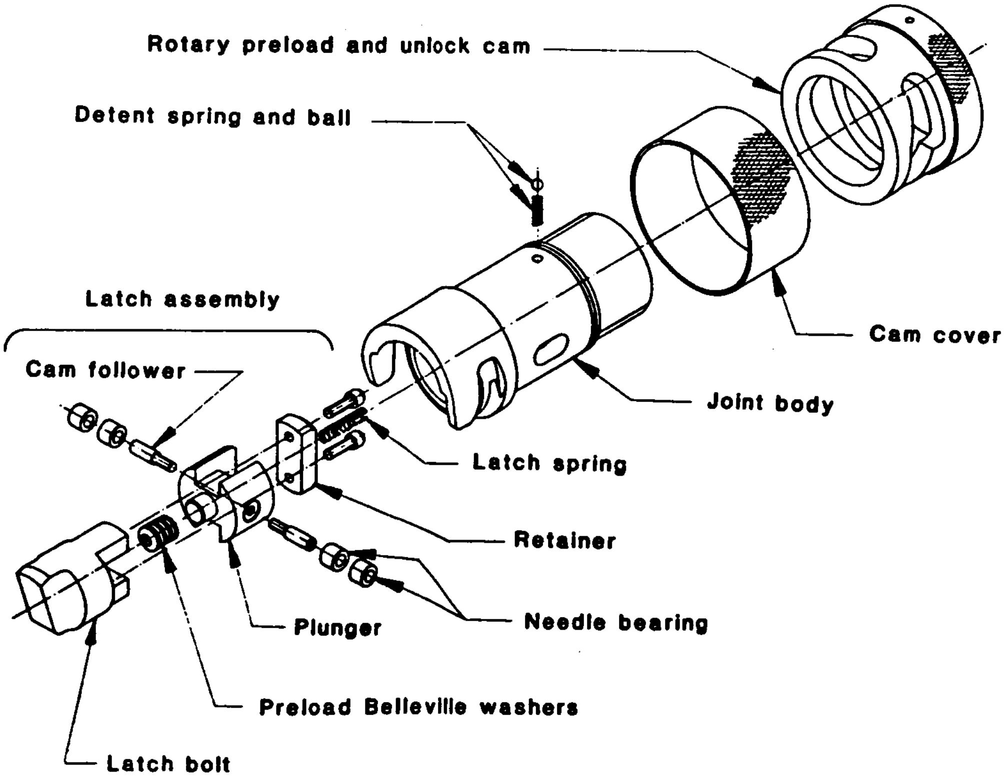


Figure 4.3.1-2 Preloaded Erectable Strut Joint--Exploded View (LaRC Concepts Under Development)

The MRMS provides manipulating capability for positioning Space Station subsystems components. The MRMS provides two Mobile Foot Restraint (MFR) platforms to position the astronauts during EVA erection and/or servicing of the Space Station. The astronaut may control his MFR platform much like a utility serviceman operating a "Cherry Picker" bucket (**Figure 4.3.1-3, Reference 18**).

The truss structure spherical nodes (**Figure 4.3.1-4**) will also provide attachment locations to secure platforms, manned modules, and experiment stations inside the truss structure to provide center of gravity location control and not interfere with the operational clearances required for the MRMS.

The astronaut assembly concept has been demonstrated using neutral buoyancy tests and in-space erection-disassembly studies with good correlation of the performance times (**Reference 19**). The anticipated assembly time for a 1,200 tubular element dual keel Space Station truss structure is 20 hours based on one minute per element.

The habitation and laboratory modules will be fabricated from aluminum alloy and welded to assure leak tightness.

4.3.2 Advanced Space Station Materials Technology Trends

The advanced Space Station will require improved structural materials to assure fabricability of structures and enclosures that possess long life during prelaunch, Earth storage, and on-orbit space environments. The selection of materials suitable for each application will require consideration of the following factors:

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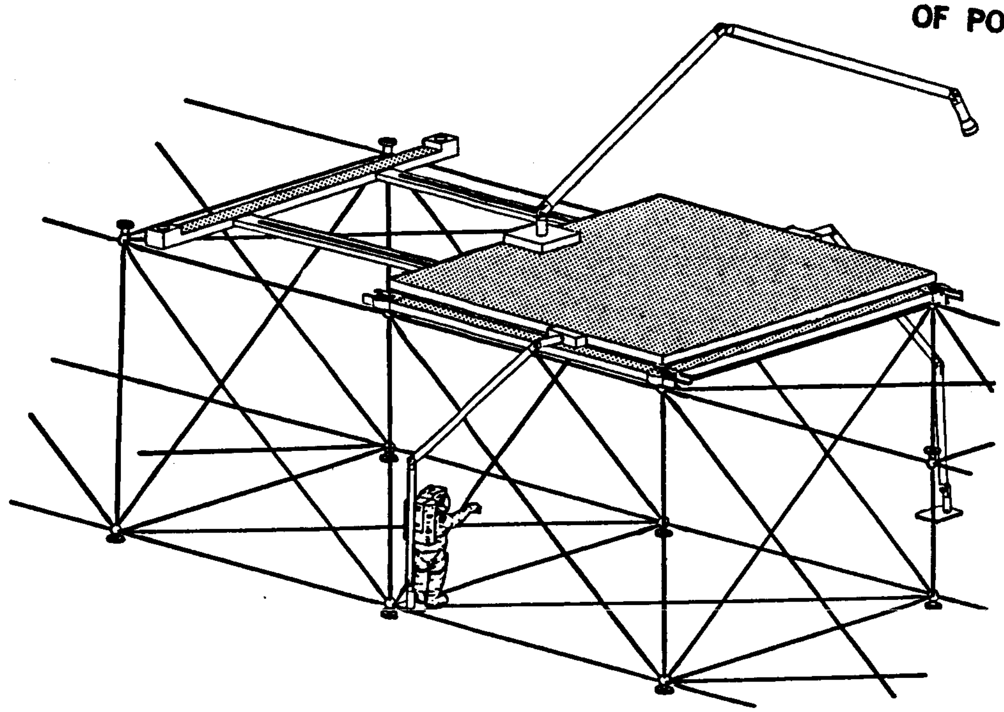


Figure 4.3.1-3 Mobile Remote Manipulator System (Reference 18)

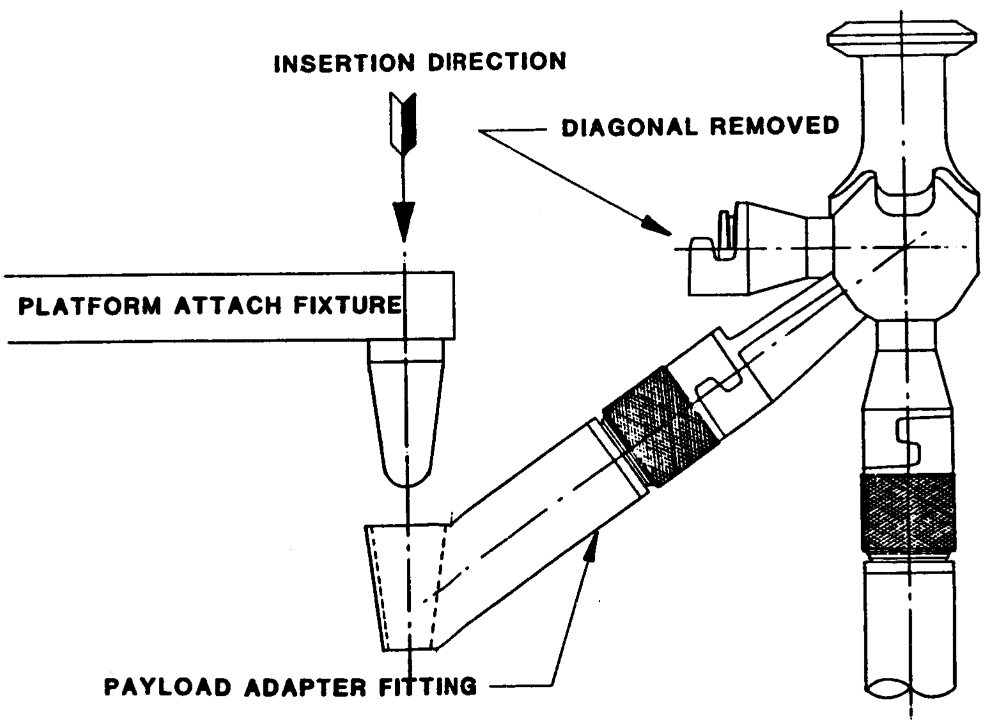


**Figure 4.3.1-4 Platform Attachment Method
(LaRC Concepts Under Development)**

1. Definition of the requirements for a specific material application
2. Determination of the effects of critical environmental conditions on the candidate material's properties and possible interactions with other systems
3. Qualification of the material for its intended use

A summary of damage mechanisms of materials resulting from a space environment is provided in **Table 4.3.2-1 (Reference 3)**.

Structural composites consisting of an organic resin matrix reinforced with inorganic fibers offer high specific stiffness and specific strength with adequate structural integrity for a variety of space applications. The space durability of currently available resin matrix composites is projected as approximately eleven years. Lifetimes of fifteen to thirty years in space are forecast using improved materials and processing methods (**Figure 4.3.2-1, Reference 3**).

Polyimide resin matrix composite materials offer promise for increasing the maximum service temperature of composite structures from the state-of-the-art use temperature of 450 K to possibly 720 K by 1990 as predicted in **Figure 4.3.2-2 (Reference 3)**.

Metal matrix composites (MMC) composed of high modulus graphite fibers embedded in an aluminum or magnesium matrix offer materials having high specific stiffness, high thermal deformation resistance, low coefficient of thermal expansion, and negligible outgassing. Large space structures and space antenna systems require high dimensional stability to maintain the system's alignment accuracy. **Figure 4.3.2-3** compares the specific stiffness

TABLE 4.3.2-1 DAMAGE MECHANISMS FROM THE SPACE ENVIRONMENT (REFERENCE 3)

Environmental Element	Damage
Ultraviolet Radiation (Solar Electromagnetic)	- Creation of lattice defects in crystalline materials - Chain scission of organic materials Free radical formation Color centers - Crosslinking of organic materials
Charged Particle Radiation (Trapped radiation, solar winds, solar event particles, cosmic rays)	- Creation of lattice defects in crystalline materials Recombination centers Absorption centers - Chain scission of organic materials - Crosslinking of organic materials - Secondary radiation damage
Pressure (Atmospheric)	- Volatilization of low vapor pressure fractions and materials - Diffusion - Vacuum welding
Thermal (Solar Electromagnetic)	- Mechanical degradation, softening or embrittlement - Chemical degradation - Acceleration or deceleration of above environmental effects
Micrometeoroid	- Mechanical Fracture or puncture
Electrodynamic Interactions	- Spacecraft charging
Atomic Oxygen Bombardment	- Oxidized surface recession

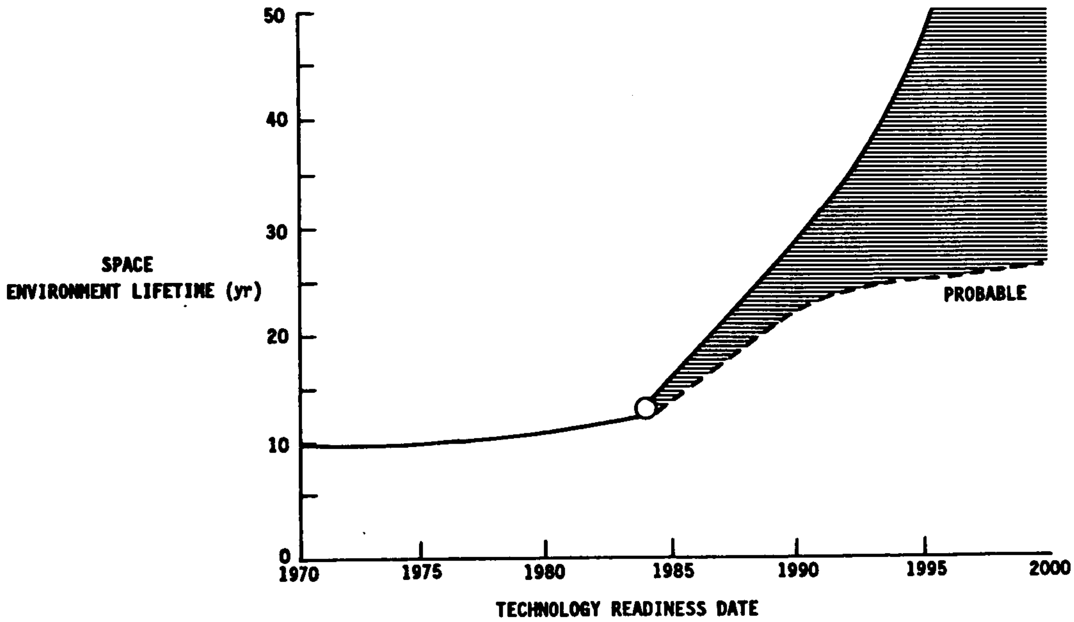


Figure 4.3.2-1 Space Environment Lifetime of Resin Matrix Composites (Reference 3)

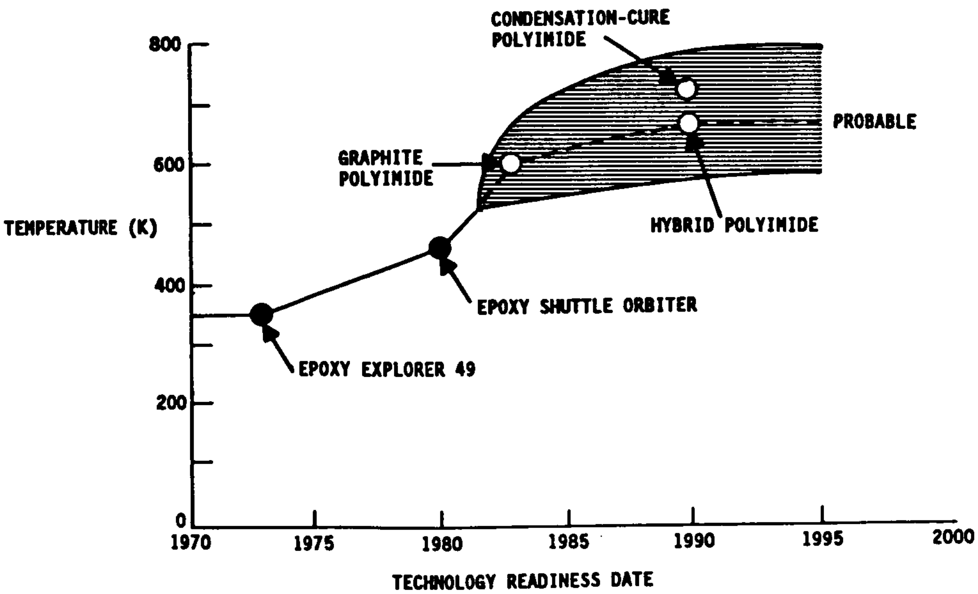


Figure 4.3.2-2 Maximum Usable Non-Metallic Service Temperature (Reference 3)

versus thermal deformation resistance of several spacecraft structural materials (**Reference** 3).

Space structures' weight reductions of 20 to 50 percent are projected by the year 2000 using advanced composite materials with improved structural analysis, design, and assembly concepts (**Figure 4.3.2-4, Reference** 3).

Earth manufactured structural elements will be designed for on-orbit assembly for large structures using assembly aides such as those described in **Table 4.3.2-2**. The free-flying teleoperators with man-in-the-loop remote controls appear to be very versatile for non-repetitive assembly tasks and to minimize extravehicular activities.

NASA LaRC is studying a space spider crane with four 60-foot legs and two arms. The spider crane would be able to assemble various elements of the Space Station and maneuver around complicated station elements such as solar arrays or radiators (**Figure 4.3.2-5**). The crane would be battery powered and controlled remotely by computer or astronaut. A rail system has been considered at the Goddard Space Flight Center for transport of a manned extravehicular robot to install and service utilities and payloads from within the geometry of the Space Station truss structure (**Figure 4.3.2-6**).

4.3.3 Candidate Advanced Structures and Materials Subsystem

A modified tetrahedral truss structure appears as a valid method of construction for the Space Station using free-flying teleoperators. Structural tubular elements of graphite fiber reinforced polyimide resin, or graphite fiber embedded in magnesium or aluminum are candidate structural composite materials.

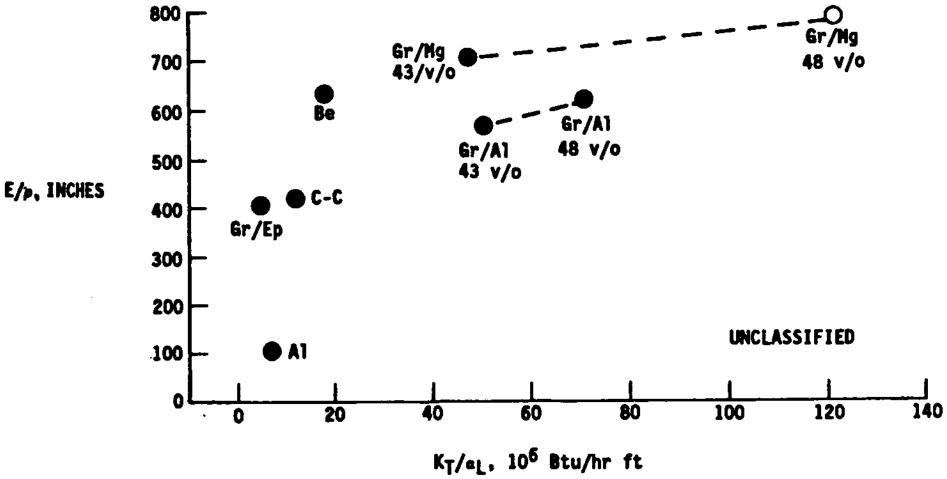


Figure 4.3.2-3 Specific Stiffness, E/ρ, Versus Thermal Deformation Resistance, K_T/α_L, for Spacecraft Structural Materials (Reference 3)

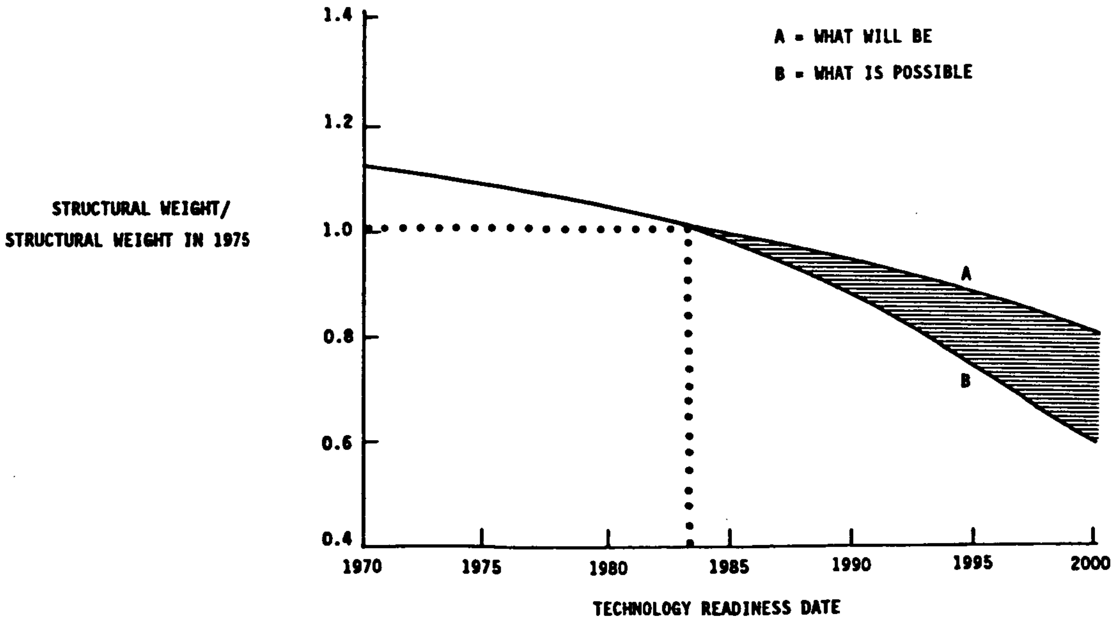
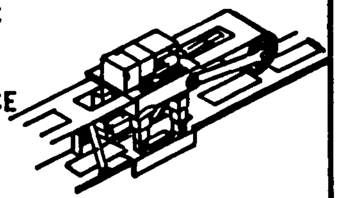
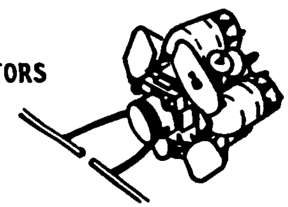
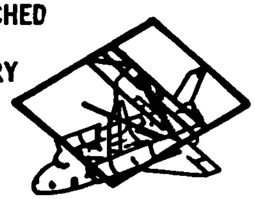
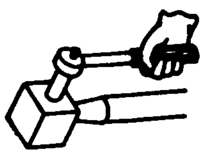


Figure 4.3.2-4 Structural Weight Reduction for Space Systems (Reference 3)

TABLE 4.3.2-2 ASSEMBLY AIDS AND HUMAN INVOLVEMENT (REFERENCE 3)

OPERATIONS/ASSEMBLY AIDS	CREW INVOLVEMENT	APPLICATION ADVANTAGES
AUTOMATIC ASSEMBLY MACHINES (EG "SPACE SPIDER") 	• ESTABLISH INITIAL CONDITIONS • START AND STOP AUTOMATIC SEQUENCES • MONITOR EXECUTION, TROUBLE-SHOOT HARDWARE AND SOFTWARE	• LARGE SCALE OPERATIONS • REMOTE OPERATIONS • LOW OR CONTROLLED CONSTRUCTION LOADS
FREE FLYING TELEOPERATORS 	• PILOT TRANSPORT VEHICLE • CONTROL MANIPULATOR ARMS • MONITOR SYSTEM STATUS, TROUBLE-SHOOT HARDWARE, SOFTWARE	• REMOTE OPERATIONS • NON-REPETITIOUS OPERATIONS • TASKS WITH HIGH DEXTERITY REQUIREMENTS • CAN BE GROUND CONTROLLED
SHUTTLE-ATTACHED MANIPULATORS CRANES, CHERRY PICKERS 	• PROVIDE STABLE STS PLATFORM FOR CONSTRUCTION OPERATIONS • OPERATE MANIPULATOR TO UNSTOW POSITION AND MATE STRUCTURAL ELEMENTS	• LOCAL (LOW EARTH ORBIT) CONSTRUCTION • CONTROLLED CONSTRUCTION FORCES • CONTINGENCY EVA POSSIBLE
HAND TOOLS & AIDS FOR EVA USE 	• EVA CREWMAN SERVES DIRECTLY AS SPACE CONSTRUCTION WORKER	• MINIMAL COST FOR EQUIPMENT DEVELOPMENT--EXISTING CAPABILITY • HIGH FLEXIBILITY FOR UNFORESEEN TASKS • LOCAL CONSTRUCTION, SMALLER SCALE CONSTRUCTION

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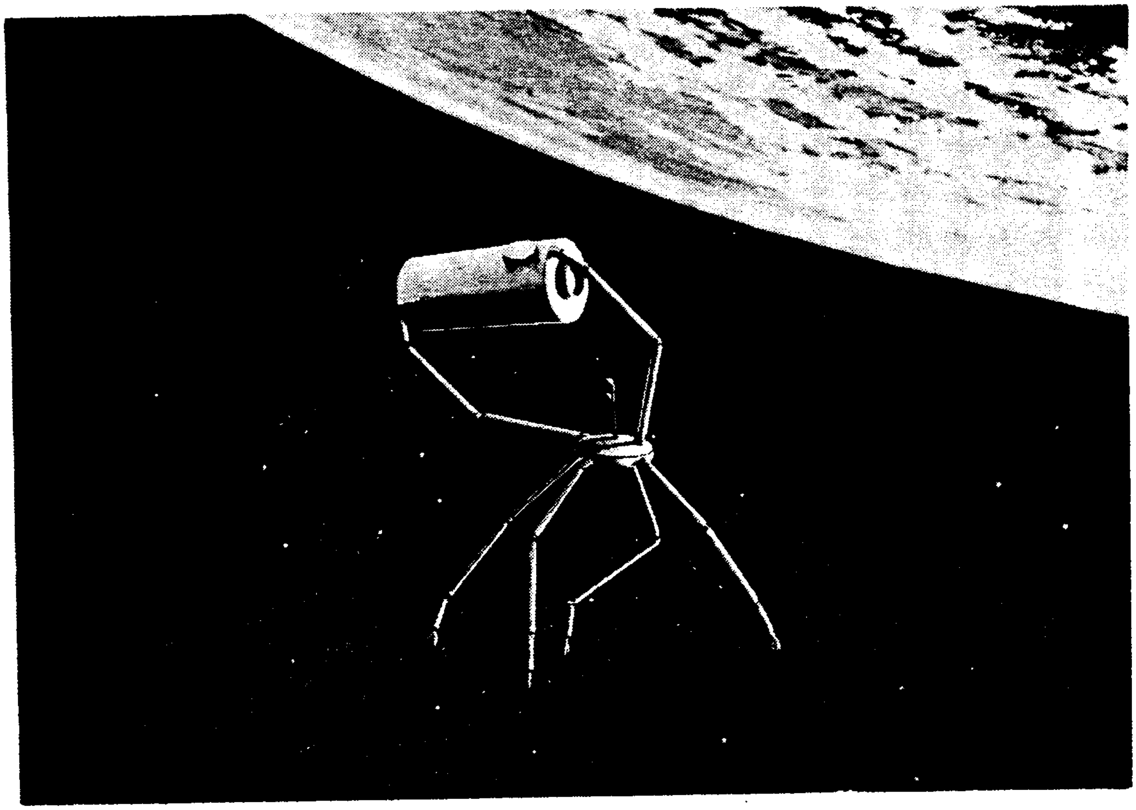


Figure 4.3.2-5 Space Spider Crane (Under Study at LaRC)

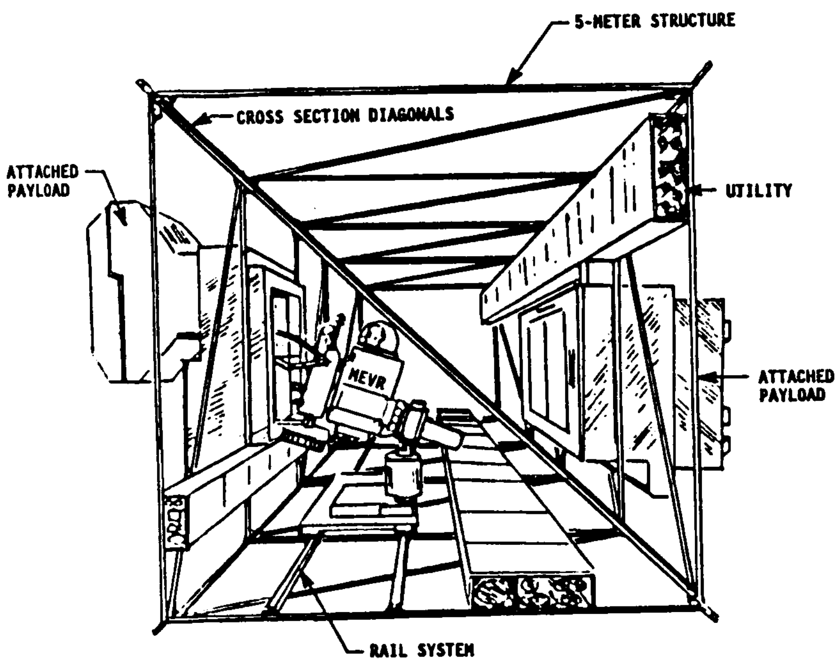


Figure 4.3.2-6. Mobile Rail System Concept (Under Study At GSFC)

Inflatable structures can be carried deflated and folded into space. The structure would be inflated in space on command and the resin impregnant of the structure's reinforcements would harden in the space environment.

Large rotating seals for maintaining one earth atmosphere of pressure within a rotating Space Station would provide a shirtsleeve work environment for the astronauts.

Completely assembled laboratory and habitation modules weighing up to 150,000 pounds could be delivered to orbit by way of a heavy lift cargo vehicle.

A helical-wrap large diameter tube could be stowed in a cargo vehicle whereby the helical band would be telescoped within itself to achieve a high packing density. The tube would be telescopically extended in space with a locking and sealing of the helical seam to form a gas tight cylindrical structure.

A brief review of some factors to be considered in selecting materials for Space Station application is given in the Appendix.

4.4 On-board Propulsion Subsystem

The on-board propulsion system provides the thrust capabilities to accomplish reboost, maintain the attitude, and execute avoidance maneuvers. A review of the future space missions shows the need for a major Space Station in orbit at 500 km altitude with a 28° inclination. Orbital flight requirements for higher (up to GEO) altitudes or at other orbit inclinations would be served by auxiliary platforms. Therefore, for the Space Station, reboost represents the principal continuing requirement for thrust. The review of missions does imply a significant Space Station participation in the assembly, checkout, and deployment operations for advanced missions. In such operations, the thrust requirements to support docking, erection or assembly, and undockings could each expand by more than an order of magnitude. The considerations for Space Station evasive action or avoidance maneuvers anticipate modest motions performed at low velocities. Any hostile action or threat would be countered by other than evasive maneuvering of the Space Station itself.

The descriptions and assessments of propulsion system technologies which follow were generated at the same time the propulsion system for the IOC Space Station received a major technical review which changed the baseline from monopropellant hydrazine to O_2-H_2. The discussions, descriptions, and comparisons that pertain to hydrazine continue as valid. The shift to an O_2-H_2 based propellant system recognizes the cited advantages and accepts the identified developmental achievements as part of the planned effort to produce the IOC Space Station.

4.4.1 State-of-the-Art

The propulsion system initially selected for the IOC Space Station utilized the established technology presented by catalytic combustion of monopropellant hydrazine (N_2H_4) (**Reference 6**). The selection of hydrazine is a workable compromise to achieve a straightforward operation of an established system at a modest cost in fuel weight and resupply requirements. **Table 4.4.1-1** summarizes the pertinent performance requirements and features for the system. The continuing design refinements underway for the Station anticipate changes in the impulse (and propellant weight) values listed, with the differences as fractions of the present

TABLE 4.4.1-1 SPACE STATION BASELINE PROPULSION SYSTEM UTILIZING MONOPROPELLANT HYDRAZINE, AT A SPECIFIC IMPULSE OF 220 SEC (FROM REFERENCE 6)

A. THRUST AND IMPULSE PERFORMANCE REQUIREMENTS

Parameter	Impulse Lbf. Sec.	Hydrazine Weight Lb.
1. Reboost, after 90 days at 270 NM (500 km)	483,000	2,200
2. Orbiter Dock; Undock	26,000	120
3. Attitude Control Contingency	147,000	670
4. Collision Avoidance 5 ft/sec Contingency	61,500	280
5. Altitude Transfer 20 NM Contingency	831,000	3,780
Total On-Board Propellant		7,050
Contingency On Board	1,039,500	4,730
Minimum Resupply	509,000	2,320

B. TANKAGE AND OPERATIONS

1. No. of 40" Diameter Tanks	9 Total, 6 Contingency, 3 Resupply
2. Tank Supply Pressure Range	100-300 psi
3. Thrusters Arrangement	4 Locations, 3 each direction, 36 total
4. Thruster Force Range	25-75 pounds

values. The present system has no defined synergy with any of the other systems on the Station and draws upon the Station's supply for both operating electrical power and nitrogen to pressurize the fuel tanks. The pertinent features of the system are described in terms of the thrusters, propellant storage, and control.

4.4.1.1 Thrusters

The individual thruster design utilizes a catalytic bed unit which can provide from 25 to 75 pounds of force in proportion to a blowdown fuel supply pressure ranging from 100 to 300 psi. A triple redundancy results from clusters having three independent units operating in three directions to provide nine thrusters at each of four locations (36 thrusters total). Reboost operations will establish the life requirements for both the catalyst beds and nozzles and anticipate some configuration development for the catalyst beds. The concept of on-board, in-place spare thrusters (e.g., extra units in each cluster) has been addressed and remains as a life-extending option. Uprating by heated beds represents the near-term development effort for an advanced system and could offer up to a 35 percent improvement in specific impulse (**Reference 20**).

4.4.1.2 Propellant Storage and Distribution

The provisions for propellant storage utilize spherical tanks 40 inches in diameter. The Space Station includes a fixed on-board tank cluster which accommodates the contingency resource (nominally six tanks) (see **Figure 4.4.1-1**). Resupply will transport tanks sufficient to perform reboost and docking (nominally three tanks) plus any additional tanks needed to

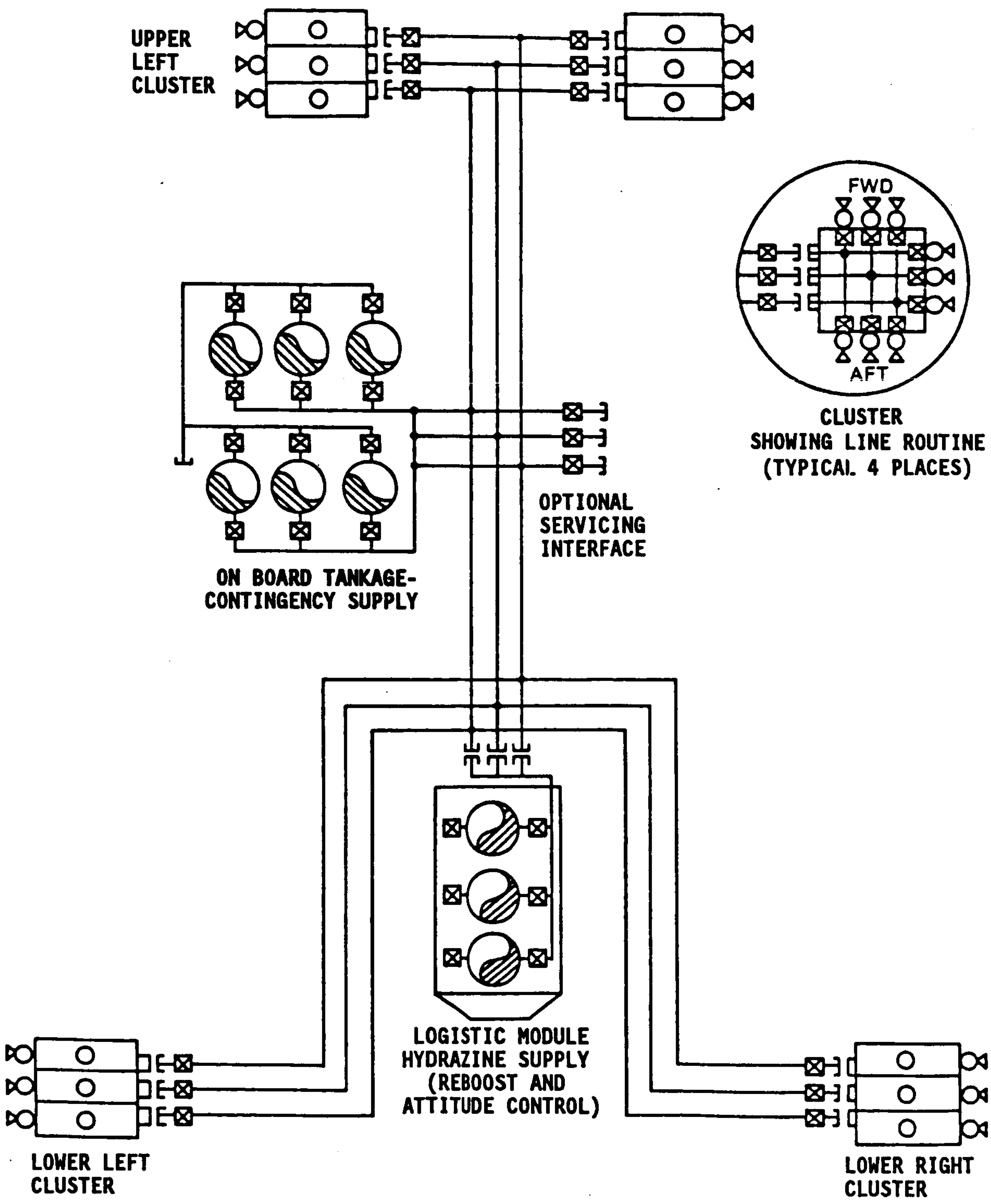


Figure 4.4.1-1 Reference Configuration Propulsion System with Approximate Equipment Locations (Reference 6)

replenish the contingency. The concept presented envisions remote handling of all fuel servicing activities (no EVA for connect, disconnect). The tanks all include internal diaphragms for fluid control with the ullage space filled and pressurized by GN_2 from the central supply (LN_2 on-board storage or an auxiliary decomposition of N_2H_4). In operation, the ullage pressure provides the distribution forces and the blowdown pressures at the individual thrusters which determine the actual thrust levels achieved. The distribution system provides triple redundant lines to each set of clusters such that one line feeds three thrusters, one for each for thrust direction at that location. The distribution includes solenoid valves that permit:

1. Isolation of each tank
2. Propellant feed to all thrusters from any tank
3. Propellant transfer between tanks

Ullage pressure provides the driving forces for all propellant movements including transfer between tanks. Therefore, the system is designed to operate at tank pressures above 300 psi. Hydrazine has some limits for temperatures during storage and transfer. The tanks and distribution lines, therefore, include heaters for temperature control. These draw their power from the on-board supply.

4.4.1.3 Thrust Control

Solenoid valves located at the inlet to each thruster provide the means for initiating and terminating thrust forces. Impulse control becomes a combination of ullage pressure and thrust duration. The concept of feeding all thrusters from the same tank minimizes any effects due to changes in the supply pressure; the distribution lines have been sized to balance or minimize flow pressure losses. The operation of the system will permit individual firing and timing for each thruster. The actual firing-sequence control commands appear as the output from an on-board computer algorithm contained within the navigation and control system. The anticipated operations foresee only modest thruster usage for attitude control or docking. Reboost presents the principal utilization with burn times of several minutes. The contingency requirements for velocity change or orbit altitude increase can involve longer times, but they are not scheduled events.

4.4.1.4 Summary of the State-of-the-Art

In summary, the propulsion system utilizes a straightforward established technology which will require a minimum of configuration-specific development for the Space Station application. In exchange, the Space Station accepts the extra increment of supply weight and the particular safety-related handling constraints associated with hydrazine. Reliability utilizes triple redundancies and accepts the additional number of valves and valve controls which result. The system shows no synergistic participations beyond the potential use of N_2H_4 decomposition for N_2 replenishment. Actually, the system is dependent in that it makes demands on electrical power. In total, the system appears to be an effective compromise which reflects the diverging requirements presented by the Space Station. In addition, the system offers a near-term potential performance improvement of as much as 30 percent in specific impulse by utilizing heated catalyst beds (**Reference 20**). Since thruster change-out is considered in the IOC design, the potential uprating appears both attractive and attainable to the point of justifying a continuing development for enhanced performance monopropellant units in the 20- to 100-pound force range.

4.4.2 Review of Status and Technology for Propulsion Subsystem Candidates

The candidates for Space Station on-board propulsion system applications can be summarized in terms of chemical, electrical, and other. **Table 4.4.2-1** lists the present candidates in terms of the pertinent performance and application considerations. For discussion purposes, each of the candidates has been assigned a ranking relative to development requirements and compatibility assessments. The ranking criteria appear in **Table 4.4.2-2.** The organization of the table and assignments of technology which follow reflect the energy source which effectively provides the acceleration to the ejected matter. Chemical reaction obviously involves the energies available through combustion. The electrical systems apply the major portion of the thrust energy directly from an on-board electrical power source. The "other" category involves interactions that appear to have an intermediary effect in the application of energy to the exhaust effluent.

A survey of the candidates underscores the selection of monopropellant hydrazine as the IOC propellant. The components of the hydrazine system all exist and have proven capabilities from previous space applications which, together with the straightforward handling and tankage logistics, more than offset the performance penalty.

TABLE 4.4.2-1 SUMMARY OF CANDIDATE PROPULSION SYSTEMS FOR ADVANCED SPACE STATION APPLICATION

Propulsion Systems Propellant	Thrust Range	Specific Impulse (Isp) Sec	Effluent or Exhaust Products	Comments Pertinent to Space Station	Technology Assessment	Compatibility Assessment
A. CHEMICAL REACTION						
1. Hydrazine Monopropellant (N_2H_4)	0-4000N (0-1000lbs)	220-300	N_2, NH_3, H_2	Present baseline, Isp to 300 sec. obtained by heated catalyst beds; near-term development	7	2
2. Hypergolic Bi-propellants N_2O_4-$N_2H_3CH_3$ (NTO-MMH) and	0-10^4N (0-10^4lbs)	300-400	N_2, H_2O, CO_2	Presently used hypergolic, N_2O_4 ignition residues are toxic and corrosive	7	3
N_2O_4-$N_2H_2(CH_3)_2$ (NTO-UDMH)	to 10^5N (10^5lbs)	300-400	N_2, H_2O, CO_2	Present hypergolic for shuttle OMS and RCS systems	7	3
3. F_2 with N_2H_4 or H_2	to 10^6N (10^6lbs)	to 500	HF, N_2	HF is corrosive and toxic	5	4b, c
4. O_2 with H_2, CH_4, or N_2H_4	10^4-10^6N (10^4-10^6lbs)	350-450	H_2O, CO_2, N_2	Shuttle main engine system. Presently no low thrust engines available. Offers synergy with life support for on-orbit H_2, O_2 supply.	7	1
B. ELECTRICAL						
1. Electrostatic Ion	0-2.5N (0-0.5lbs)	2000-6500	Hg, Cs, Xe, Kr	Limited to low thrust systems.	5	4a
2. Resistojet, NH_3, H_2O, H_2, CO_2	0-50N (0-10lbs)	350-950	N_2, H_2, H_2O, CO_2	Attractive for synergy with life support.	5	4a

TABLE 4.4.2-1 SUMMARY OF CANDIDATE PROPULSION SYSTEMS FOR ADVANCED SPACE STATION APPLICATION (CONCLUDED)

Propulsion Systems Propellant	Thrust Range	Specific Impulse (Isp) Sec	Effluent or Exhaust Products	Comments Pertinent to Space Station	Technology Assessment	Compatibility Assessment
3. Arcjet, NH_3, H_2O, H_2, CO_2	0-50N (0-10lbs)	500-2000	N_2, H_2, O_2, C	Attractive for synergy with life support.	4	4a
4. Magnetoplasmodynamic (MPD)	0-500N (0-100lbs)	1000-7000	A, Xe, Ne	Presently limited to noble gasses.	3	3, 4a
C. OTHER CONCEPTS						
1. Electromagnetic Mass Accelerators (Rail Guns)	$0\text{-}10^5$N ($0\text{-}10^4$lbs)	1000-3000	Solids	Concern for debris in LEO. Shows potential for synergy with life support.	3	4c
2. Laser Heated Ejector	$0\text{-}10^5$N ($0\text{-}10^4$lbs)	1000-3000	H_2, C, O_2, N_2	Potential for synergy with ECLSS.	3	4c
3. Mass Conversion as Anti-matter Interactions	$0\text{-}10^6$N ($0\text{-}10^6$lbs)	to 10^7	H, H_2, and Sub-atomic Particles	Clean exhaust at relativistic velocities.	1	4c
4. Free Radical	$0\text{-}10^6$N ($0\text{-}10^6$lbs)	to 10^5	H_2, H_2O	Clean exhaust.	2	4c

TABLE 4.4.2-2 PROPULSION SYSTEM RANKING CRITERIA (REFERENCE 3)

A. TECHNOLOGY ASSESSMENT		
General Technology Readiness Levels		Propulsion System Equivalent
Level 1	Basic Principles Observed and Reported	Requires significant scientific advance. No date for accomplishment.
Level 2	Conceptual Design Formulated	Initial analysis shows potential application. More than 10-year development.
Level 3	Conceptual Design Tested Analytically or Experimentally	System has been operated; up to one decade of development required.
Level 4	Critical Function/Characteristic Demonstrated	New system in development. Estimate 5 years minimum time to readiness.
Level 5	Component/Breadboard Tested in Relevant Environment	System available in less than 5 years.
Level 6	Prototype/Engineering Model Tested in Relevant Environment	Technology is established. System ready for flight test evaluation. Adaptations available in less than 5 years.
Level 7	Engineering Model Tested in Space	Technology is mature. System operating on existing spacecraft. Adaptations available in less than 5 years.

B. COMPATIBILITY ASSESSMENT	
Class 1	Thrust and Exhaust products are both compatible. System offers potential synergies with Life Support or others which could simplify on-board operations and/or logistic support.
Class 2	Thrust and Exhaust products are compatible. Little or no synergy opportunity.
Class 3	Thrust and Exhaust products are compatible. On-board operations or logistics would become more complex.
Class 4	Concern or potential limitation due to one or more of the following: a. Thrust Level b. Exhaust Product c. Complexity in operations or supply

4.4.2.1 Chemical Propulsion Systems

The chemical propulsion candidates present the best developed systems available at this time. The energies available are those of combustion as oxidation or combustional breakdown and are well defined for all of the reactions involved. Improvements in specific thrust, therefore, relate to improvements in translating the energy of combustion into kinetic energy in the effluent streams; e.g., burn and exhaust at higher temperature. These considerations lead to development of improved pumps or pressurants for the fuel supply, higher operating pressures in the combustion chamber, and improved resistance to erosion or degradation of nozzles when subjected to the flowing hot gasses. All of the chemical systems described have been built and tested, most have flown in one form or another, and three represent the major storable-propellant systems presently employed in space vehicles. Therefore, within the chemical-based propulsion system summarized in **Table 4.4.2-1**, the lower value for Isp corresponds to present capabilities; the upper value represents a plateau of potential achievement (**Reference** 3).

Monopropellant Hydrazine

The catalytic burning of N_2H_4 represents the mature technology for modest thrust range (25-250 pounds) applications. The production storage and control systems for this fuel have existed for nearly two decades. On-orbit storage times have exceeded several years. For Space Station, the developments must address high purity production of the N_2H_4 and operating life for the catalytic beds. The presently defined specific impulse of 220 seconds is well established. Development of heated bed combustors is underway (**Reference 20**) and shows a potential for increasing Isp to 300 seconds. A continuation of this development should achieve the goal in sufficient time for application to the IOC Space Station or at least an early update. The completion of the thermal augmentation developments appears as the last significant performance increase for the monopropellant system. Small improvements may continue; however, an Isp of about 300 seconds appears as a near-limit for the technology. Monopropellant hydrazine will remain the base for comparison in evaluating any other candidate propulsion system.

The opportunity for a synergistic interaction has been addressed by Boeing (**Reference 21**) as use of the N_2H_4 to supply makeup N_2 needed to resupply the losses in the cabin atmosphere. The catalytic breakdown of the hydrazine and recovery of the N_2 has the potential to eliminate the need for transport of LN_2. A makeup rate of five pounds per day or 500 pounds over a resupply period amounts to about half a tank of N_2H_4. The synergy would result in some extra H_2 (utilization not defined) plus the need for on-board gas separators and compressors.

The Hypergolics, NTO-MMH or UDMH [N_2O_4-$N_2H_3CH_3$ or $N_2H_2(CH_3)_2$]

The hypergolics are well understood storable bipropellants; both have been used in space flights. The NTO-UDMH option has an extensive applications history, including storable boosters (Titan II), multiburn long-life space probes (Viking Orbiter), and maneuver-attitude control systems (Shuttle OMS-RCS). The hypergolics as utilized in the Shuttle RCS demonstrate pulsed thrust operations in the range 25 pounds to 200 pounds. The present hypergolics provide specific impulses up to 330 seconds. The potential for increasing performance requires operation at higher chamber pressures and an improvement in nozzle performance. The vernier engines on the Shuttle (25-pound thrust) could be the starting point for a development program which could achieve a 20-point increase in performance to an Isp of 350 seconds. It is estimated that a concentrated development program could provide advanced propulsion capability in less than five years. On the other hand, the performance margin over the competitive monopropellant would not appear to justify the extra complexity in tankage or resupply unless the N_2O_4 became a major element in the makeup of N_2 and O_2 for life support. A chemical decomposition and separation that yielded 500 pounds of N_2 would also provide more than 1100 pounds of O_2. A comparison of potential synergies relative to the present system permits an assessment of value for justifying the development of the application.

1. The present system (**Table 4.4.1-1**) shows a total of 7,050 pounds of N_2H_4 on-board with 2,320 pounds minimum at each resupply. The on-board propellant storage consists of nine tanks, each 40 inches in diameter.

2. In the case of N_2H_4 augmented to produce an Isp of 300 seconds, the reduction in propellant requirement would amount to about 1,900 pounds and 600 pounds less at each resupply. If the N_2H_4 provided 500 pounds of replenishment N_2, the total resupply requirement would still be 100 pounds less than the present baseline value.

3. In the case of hypergolics at an Isp of 360 seconds, the total propellant weights would become 4,200 pounds, and the resupply would become 1,420 pounds. If N_2O_4 became the source for N_2 replenishment, 500 pounds of N_2 require about 1,600 pounds of N_2O_4. The resupply requirement would then

increase to 3,020 pounds. However, the 1,100 pounds of O_2 would be the 90-day requirement for a six-man crew.

The synergies offered are both attractive for an update of the present Space Station. The use of N_2H_4 as an N_2 source offers a means to eliminate the need for LN_2 resupply. The use of the hypergolics offers a means to eliminate the need for LN_2 and LO_2 and the need for recycling of CO_2 or the electrolysis of water. In a power-limited Space Station, the use of N_2O_4 with its extra complexities in tankage could be offset by the simplified life support system requirement (**Reference 21**).

<u>Fluorine Bipropellants F_2-H_2, CH_4, N_2H_4</u>

Within the options for chemical propellants, the fluorine reactions provide the maximum energies and translate into the maximum values for specific thrust. Values of Isp to 500 seconds reflect the fluorine-hydrogen reaction. The improvements in performance bring attendant problems of handling a toxic, corrosive liquid and the chemical effects of HF in the exhaust stream. The nuclear industry has developed a comprehensive capability for handling and controlling fluorine in all of its forms and phases (UF_6 is the transport medium for gaseous diffusion enrichment separation of uranium isotopes); however, these techniques may not be directly applicable to flight support or on-orbit operations. The co-propellants of H_2 and CH_4 have the potential for synergy with the life support system as H_2 from electrolysis of water or CH_4 as an interim product in the Sabatier process for reduction of CO_2 (**Reference 22**). In either case, the presence of HF as an exhaust product appears to preclude fluorine as a candidate for an on-board propulsion system. On the other hand, fluorine-based bipropellants should be considered as candidates for the propulsion systems used in spacecraft assembled aboard the Space Station. Therefore, the Space Station should be capable of handling and storing tanked fluorine as part of a spacecraft on-orbit erection and deployment sequence.

Oxygen Bipropellants, O_2-N_2H_4, CH_4-H_2

The oxygen based bipropellants offer the combination of high specific impulse and potential for synergy with the life support system. The products of combustion for these combinations are compatible with long-term exposures for the Space Station; the only concern may arise from O_2-N_2H_4 where the potential exists for some NO_x residuals. All of the systems have been operated with O_2-H_2 performing as the main propulsion system for the Shuttle.

These systems may be considered as available technology but not available as equipment items with the particular thrust levels or control systems which correspond to the Space Station applications. Thrusters in the range from 25 to 75 pounds have not been built. The high pressure fuel supply pumps required for optimum engine performance do not exist; the valves and control systems for low-thrust, minutes-of-burn applications have not been configured. No obvious barriers appear to inhibit developing such equipment; a focused development of the O_2-H_2 or O_2-CH_4 systems could support an update of the IOC Space Station. Both offer the potential for synergy with the Life Support System, in particular the utilization of on-board electrolysis of water for an O_2 supply and the Sabatier process for reducing CO_2 which yields CH_4 as an interim product. As indicated in the comparison for the hypergolics, O_2 replenishment for a crew of six would process about 14 pounds of water per day (12 pounds of O_2). At an Isp of

440 seconds, the reboost requirement corresponds to about 13 pounds of water per day. The reboost propellant for an O_2-H_2 system would utilize the necessary redundant capacity incorporated into the main O_2 regeneration equipment.

A comparison of tankage shows a considerable weight savings in either a cryogenic or water-supplied approach. For an Isp of 440 seconds, the resupply is half the present requirement or 1,160 pounds, either as 1,030 pounds of LO_2 plus 130 pounds of LH_2 or as water. As water, the resupply amounts to one 40-inch diameter tank; as cryogenics, the resupply becomes one tank for O_2 and two tanks for H_2. The on-board storage tanks would not reflect the same advantage. The need to maintain the contingency fuel in cryostorage amounts to five cryogenic tanks as compared to one temperature-controlled tank for the hydrazine.

In summary, the O_2-H_2 or O_2-CH_4 propulsion systems rank high as candidates for Space Station on-board applications, particularly if configured for synergy with a life support system based upon electrolysis of water and potentially the Sabatier process for reduction of CO_2. These propellants offer a means for simplifying the resupply requirements at the expense of electrical power for use in orbit and the need for on-board high pressure or cryogenic storage. At the present time, propulsion components do not exist in the size ranges associated with the Space Station application. No barrier has been identified which would delay such developments; Space Station quality and compatible equipment could be available within a half decade.

4.4.2.2 Electrical Propulsion Systems (**Reference** 3)

The electrical propulsion systems are characterized by generation of thrust as a direct interaction with the electrical power supplied. The interactions can be heating as in a resistojet or arc jet, electromagnetic induction as in the magnetoplasmadynamic (MPD), or accelerations of charged particles by an electric field (ion). Each of the systems shows specific thrust values which exceed those for any chemical system. On the other hand, the working medium provides very little energy of its own; therefore, electrical propulsion systems present real-time demands upon the power supply within the spacecraft. In addition, these systems are inherently low thrust configurations and have limitations on continuous operation. **Table 4.4.2-3** presents a summary of the thrust levels and electrical performance ranges available or achievable within a decade. As a comparison, the table includes a value for the thrust required to accomplish reboost as a continuous force. In addition, the table includes a value for relative electrical performance if an O_2-H_2 chemical system utilizing on-board electrolysis of water is used as the source for the propellants. The upper values for Isp as shown in **Table 4.4.2-1**, coupled with both the achievable thrust levels and electrical performance, show that a successful development program will provide system potentials for accomplishing reboost and docking at power requirements which are less than 10 percent of the available power in the IOC Space Station. Electrical propulsion applications for such operations would be defined in terms of thrust levels and duty cycles. On the other hand, these systems would not have the capability for responding to contingencies. The Space Station contingency planning envisions thrust levels in the range of 100 pounds sustained for minutes, and such

TABLE 4.4.2-3 COMPARISON OF ELECTRICAL PROPULSION SYSTEMS

System	Thrust Pounds	Electrical Performance Thrust/kWe Supplied	Applications Considerations
Ion or charged particle	0 to 2.5 N (0 to 0.5 lbs)	0.013 to 0.09 N (0.003 to 0.020 lbs)	Acceleration voltage gradient limited by arc breakdown condition
Resistojet	0 to 50 N (0 to 10 lbs)	0.13 to 0.31 N (0.03 to 0.07 lbs)	Temperature limit by material and convection heat transfer
Arc Jet	0 to 50 N (0 to 10 lbs)	0.036 to 0.18 N (0.008 to 0.04 lbs)	Materials limit in arc plasma environment
MHD	0 to 500 N (0 to 100 lbs)	0.013 to 0.09 N (0.003 to 0.02 lbs)	Materials limit in arc plasma environment
COMPARISON:			
Baseline continuous thrust for reboost	0.27 N 0.062 lbs		(483,000 lb. sec. delivered as a continuous thrust for 90 days)
O_2-H_2 chemical from on-board electrolysis of H_2O		0.202 N 0.0452 lbs	(Electrolysis at 70% efficiency, thruster Isp of 440 sec.)

performance capabilities are not possible with electrical systems. The Space Station utilization for electrical propulsion systems must be addressed in terms of candidates for low-force applications used in combination with a standby higher-force system for contingencies.

<u>Electrostatic Field Acceleration Systems</u> (**Reference 23**)

Thrust generation by an electrostatic field includes the acceleration of both ionized atoms (ion propulsion) or charged particles (colloids). The NASA development program has focused upon applications that require thrust levels in the millinewton (millipound) range and address precision attitude control or station keeping at GEO. These types of thrusters have the capability for relatively long-term sustained operations. The present goals focus upon improved electrical performance with the intent to reach the 0.09 (0.02 pounds) newton-per-kilowatt levels within a decade. The thrusters show attractive values for specific impulse but present inherent limitations in attainable performance. They operate most effectively with heavy atoms or colloids; therefore, not all materials can be used. In addition, three operational features either impair the electrical efficiency or limit thrust. First, all the thrust results from placing charged particles into an electric field; consequently, the system must live with limits on available field strength (arc breakdown) and accept the energy losses associated with charging the thrust media as particles or atoms. Secondly, there is a limit to the number of atoms that can be given an electric charge within the thruster. Finally, once the atom or particle leaves the accelerating field, it must be neutralized or a reverse acceleration will occur (positive ions are attracted to the negative plate from both directions). In assessing the long-term development for these types of thrusters, they will remain attractive for applications requiring low thrust. An order of magnitude increase in either thrust or electrical efficiency does not appear realistic. A colloid thruster that could eject trash generated from other on-board systems appears a possible Space Station utilization for electric-field type accelerators.

Resistojet Systems (Reference 2)

The resistojet systems may be considered as a cold gas blowdown passing through an electrically heated tube or through a grid. The heat transfer surfaces provide the means for increasing the kinetic energy in the effluent stream. Resistojets offer the best available electrical performance coupled with the least sensitivity to the propellant constituents, while at the same time providing specific impulse values which double those of chemical systems. The system has inherent limits imposed by the maximum operating temperatures for the heat transfer surfaces and the attainable convective heat transfer from the surfaces. A conservative long-term assessment of Isp improvement suggests as much as 25 percent from temperature rises, and this would translate to a 50 percent increase in electrical efficiency. To the Space Station, the resistojet provides an opportunity for attitude control thrusters and possibly a two-times-per-orbit reboost that could utilize trash gases or constituents in synergy with the life support system.

Arc Jets

The arc jet augments a cold gas blowdown by passing the gas stream through the plasma of a sustained arc. The stream temperature achieved in passage through the plasma effectively determines the output performance of the system. The temperatures within the arc will dissociate compounds into elements and produce an ionized elemental exhaust stream whose features relate to the output limits of the system. Ionization and chemical dissociations are unrecovered energy losses. Since arc plasmas exceed the vaporization temperatures for any material, sustained arcs erode the electrodes; consequently, most arc jets operate in a pulsed mode.

For a Space Station, an attractive application would utilize the erosion as a source of material for ejection and become a trash burner for overboard dumping of residuals from other systems. For instance, the Bosch process for CO_2 reduction results in elemental carbon, which could possibly become consumable electrodes in a gas blowdown arc jet.

Magnetoplasmadynamic (MPD) (Reference 24)

MPD propulsion utilizes the magnetic field generated by the current flowing through an arc to accelerate the atoms charged by the plasma of the arc. MPD thrusters utilize concentric circular electrodes (e.g., a ring and a cylinder) and create an arc at one end such that the gas flowing in the circular annulus moves into the plasma and becomes ionized. The circumferential magnetic field in the annulus as generated by the arc current provides the electromagnetic interaction that accelerates the charged atoms out of the annulus. Because of the electromagnetic interaction, the gas stream does not require the pressurization needed for resistojet or arc jet operations or the neutralizer of the ion system. On the other hand, the system requires large currents to generate the accelerating forces. The current and the plasma define the inherent limitations for MPD thrusters. The electrical power source must provide for arc current levels ranging from 5,000 to 40,000 amperes with 40,000 amperes as the current density limit consideration. The operating voltages associated with such arcs range from 10 to 50 volts DC. The instantaneous power consumption then ranges from 50 kWe upward into the megawatt levels. In the same manner as arc jets, the plasma temperatures exceed vaporization for all materials and necessitate pulsed operation. However, the best transfer of energy into the gas stream occurs at the time of initiation; therefore, MPD thrusters benefit by pulsed capacitor-discharge operations where arc times are in milliseconds at repetition rates of two to three per second.

At the present time, MPD units have only operated with argon as the flowing gas. While no limitations have been specifically identified relative to the gas utilized, the noble gases have the advantages of being both monatomic and inert. The performance projections for MPD thrusters do not account for any compromises introduced by chemical dissociations in the gas stream.

Summary of Evaluations

The electric propulsion systems show attractive specific impulses. However, thrust levels and operating limits make them marginal candidates for application to the Space Station. The propulsion systems all have other potential applications which will continue to justify development activities. The inherent limitations for these systems will keep them in the low thrust range. However, a significant development which improves electrical performance, coupled with an opportunity for synergy, may make one of these systems an attractive choice for attitude control or reboost application.

4.4.2.3 Propulsion by Other Techniques or Transfers of Energy

The four propulsion concepts listed in **Table 4.4.2-1** represent adaptations or applications of high energy sources to propulsion systems. A significant development program addresses each of the technologies but none specifically address the propulsion applications. In addition, each of these technologies must achieve a major advance before a propulsion system can be configured. The potential performance capabilities for each of these systems make them candidates for application once the technology progresses to the point where an application can be defined.

Electromagnetic Mass Accelerators

The mass accelerator offers the advantages of a controlled thrust generated by recoil from the ejection of almost any material. Launch systems based upon mass accelerators using local material appear in the descriptions of lunar base or planetary return systems. The present national efforts to improve the overall performance in both electrical power consumption and eject velocities could bring the technology into maturity within the next half decade. The concept has the potential for synergy with life support by ejecting solid materials that need an overboard dump such as the carbon from the Bosch reduction of CO_2 or other trash from crew accommodations (**References 3 and 23**).

Laser Heated Systems

A high temperature, high velocity gas stream generated by vaporizing material with a laser presents an attractive option for a propulsion system. The overall performance of the system relates to the energy efficiency of the driving laser. The present national effort for development of lasers is intended to provide systems which can produce beam energies and pulse durations compatible with a laser-heated ejection system and within the power capabilities of the Space Station. A laser heated system would have the potential for ejecting any form of trash generated on-board the Space Station and ejecting the material in elemental forms (most probably as charged ions).

Mass Conversion as Antimatter Annihilations (**Reference 25**)

Antimatter generation and antimatter interactions represent major investigations utilizing the high energy particle accelerators on earth and measurements from cosmic ray bombardments in high altitude experiments. Antimatter is a well established concept, and the annihilation interactions have been characterized for the products formed and energies released. Among the researched candidates, the proton-antiproton interaction has been identified as having the potential for controlled energy production and application to propulsion. The interaction creates energetic subatomic particles which in turn can energize a beam of protons into motion at relativistic velocities. The concept for propulsion envisions the "burning" of antiprotons in an excess of protons (hydrogen) with the mass ratio balanced to optimize the kinetic energy delivered into the exit beam of protons. The present source for antiprotons occurs with proton-proton collisions at energies above 6 GeV. The antiprotons formed can be stored in a magnetic ring in the same manner as regular protons can be stored and accelerated in cyclotrons or similar units (**Reference 26**). In assessing the availability of antimatter technology for Space Station application, the developments appear to parallel those for controlled fusion. Applications of antimatter will require major scientific advances in the technology for generation, storage, and energy controls and none permit scheduling at this time.

Free Radical Energy

The energy release, associated with free radicals (e.g., H^+-OH^-) combining to form a stable molecule, has been defined and represents an upper limit for purely chemical energy production. Free radicals have been generated and controlled in laboratory environments. The combination of particular interest involves the transformation of monatomic hydrogen into H_2 molecules and exhibits an energy about one order of magnitude higher than combustion of hydrogen with oxygen (**Reference 23**). The developments required before application to the Space Station include means for generating free radicals in quantity plus the means for containment and control of the combining reactions. The potential for application exists; however, the enabling technical achievements cannot be scheduled at this time.

4.4.3 Candidate Propulsion System for Advanced Space Station and Recommendations

The requirements for propulsion remain essentially unchanged from the those of the IOC Space Station. There will be a requirement for orbit reboost and attitude control that is best served by thrusters providing from 100 to 1,000 N (25 to 250 pounds). The requirement for contingency-based velocity changes will continue. There will be no relief from the surface contamination requirements which dictate exhaust product cleanliness. Finally, resupply will need a continuing optimization. The recommendations recognize these requirements and present a Space Station position relative to all the candidate technologies for propulsion.

The propulsion system recommended utilizes O_2-H_2 to provide for orbital reboost and attitude control supplemented by a cluster of small solid rockets to provide the contingency boost requirements. The entire system would operate in synergy with the life support system. The reboost and attitude control thrusters together with the Orbital Transfer Vehicles will utilize O_2 and H_2 supplied from the electrolysis of water in a system which supplies the makeup of atmospheric O_2 and the reduction of CO_2, respectively. The generation of propellant becomes a major utilization of on-board power. However, the electrolysis cycle may be configured to provide a means for achieving a constant load for the power system. The net effect is a near-optimum power generator operating with O_2 and H_2 produced by electrolysis in proportion to the excess electrical power available at any particular time. The storage of propellant requires maintaining some on-board cryogenics with the H_2 having some interim storage as recoverable metallic hydrides.

4.4.3.1 Development Efforts Required and Supported for O_2-H_2

The utilization of O_2-H_2 for reboost and attitude control will require the development of the following equipment items.

1. Thrusters producing 100 to 1,000 N (25 to 250 pounds) of thrust for up to 20 seconds at an Isp of 440 seconds. The units will need to show long-life capability for such operation.

2. Control elements such as valves, throttles, actuators, accumulators, etc., capable of operating with O_2 or H_2 under high pressure, low flow conditions.
3. Pumps, valves and storage systems capable of handling H_2 and O_2 generated by electrolytic cells through the steps of compression, liquification, storage, and recovery.
4. Metal hydride storage and recovery technique for H_2.
5. Remote handling and transfer of cryo tanks between the Space Station and the Orbital Transfer (or other spacecraft) Vehicle.

The propulsion system could share development efforts with the life support system for the water electrolysis cells and those elements of equipment that reclaim water for electrolysis.

4.4.3.2 Contingency Propulsion

The needs for contingency propulsion can be met by clusters of small solid propellant thrusters selected for minimal contaminants in the exhaust. Ammonium nitrate appears as the initial candidate fuel for the application. The configuration for the rocket motor envisions a reusable case that can be reloaded on-board, and resupply would consist of preformed grains and igniters.

The use of ammonium nitrate as a fuel offers the potential for synergy with the life support system as an on-board source for N_2, H_2, and H_2O through a chemical decomposition. The material shows only a modest Isp of 175 seconds; however it is produced in quantity as a constituent of commercial fertilizers.

4.4.3.3 Recommendations Relative to Other Techniques and Technologies

The present activities and developments of propulsion systems or technologies applicable to propulsion systems cannot be ignored in the course of developing improvements to current or proposed new Space Stations. Improvements will occur that may elevate a system or technique into a preferred or advantageous category; consequently, attention is required to utilize potential advantages from system technology advances.

Monopropellant Hydrazine

The efforts to uprate the present system should continue with an augmented system ready for the first update of the IOC station.

The Hypergolics N_2O_4-UDMH, MMH

The flight experiences and operation with these thrusters and their control systems should receive a continuous technical review to identify effects which would benefit (or impair) their application to the Space Station. The potential for synergy with the life support system should be included in the study recommended for hydrazine.

Fluorine Based Bipropellants

Monitor the development efforts toward defining specific requirements for Space Station on-board handling and storage.

Oxygen Based Bipropellants

The O_2-H_2 system is the recommended development (see Section 4.4.3 above). A study is recommended to determine any potential benefit from synergy with CH_4 from the Sabatier CO_2 reduction process. Evidence of significant benefit would then lead to a study toward defining a dual fuel thruster that could operate O_2-H_2 or O_2-CH_4.

Electric Systems

Monitor the results of developments for evidence of significant improvements in thrust levels or electrical efficiencies that would offer an advantage to the Space Station. An improvement in either resistojets or arc jets would lead to a study for synergy with the ejection of materials intended for overboard disposal (e.g., trash from life support).

Other Concepts

Monitor the results of research for technical advancements which would bring the concept to the maturity level necessary before a propulsion application could be configured.

4.5 Thermal Control Subsystem

Thermal management of the Advanced Space Station will be employed to regulate the temperatures of various elements and subsystems plus their environments to assure proper operating performance and reliability of Station equipment and customer payloads in space. All power generated on the Space Station must ultimately be rejected as waste heat.

The temperatures that may be encountered could range from 4 K to over 500 K with control bands ranging from 0.01 K to 100 K and heat loads or leaks ranging from 0.1 W to over 100,000 W (**Reference 3**).

4.5.1 State-of-the Art

The state-of-the-art thermal control systems currently available are directed toward the six control processes as follows:

1. Heat transport by way of pumped liquids and/or heat pipes that operate on fluid phase change.

2. Heat rejection by panels that radiate to space the heat transported to them.

3. Temperature control achieved with valves that govern the flow of thermal fluids or variable conductance heat pipes.

4. Thermal storage achieved by transferring sensible heat plus heat of fusion to appropriate substances contained within a heat exchanger.

5. Refrigeration accomplished using thermo-electric cooling, expendable coolant, or by mechanically implemented thermodynamic cycles.

6. Thermal interfaces may require quick disconnects in fluid lines and flexible hoses and rotary seals for joints that rotate. Thermal switches and mechanical joining of structure to exterior module walls coated with thermal control coatings can provide controlled heat flow paths.

The state-of-the-art for thermal control is identified in **Table 4.5.1-1** by figure of merit, and the projected performance is forecast through the year 1991 (**Reference 3**).

The Space Station (IOC) will utilize both active and passive thermal control systems. The active systems will include two-phase ammonia thermal buses, capillary pumped loops, single-phase pumped water, evaporator cold plates, and two-phase heat pipe radiators. The passive systems will include coatings and insulation to minimize supplemental heating requirements.

A centralized heat collection and transport function employs two thermal buses to transfer heat by evaporation and condensation, thereby maintaining a constant temperature over their entire lengths. One bus will

TABLE 4.5.1-1 SUMMARY OF PROJECTIONS (REFERENCE 3)

Figure of Merit	SOA	Projection Forecasted	Year
Spacecraft Thermal Power Requirements	<100 kW	100 kW	1991
Spacecraft Thermal Control Specific Power	9 W/kg	18 W/kg	1991
Radiator Specific Mass	18 kg/kW	10 kg/kW	1991
Radiative Cooler Focal Plane Temperature	75 K	60 K	1991
Heat Pipe Thermal Transport Capacity	10^5 W-in	10^7 W-in	1991
Spacecraft-Borne Cryogenic Refrigerators			
Cooling Capacity @ Temperature	1 W @ 10 K	0.1 W @ 4 K	1991
Service Life	1 yr	5 yr	1991
Connectable Thermal Interfaces			
Spillage	0.66 cm^3	None	1986
Life	500 cycles	500 cycles	1986
Rotating Thermal Joints			
Flexible Hose	10^4 cycles 180^o	$4x10^6$ cy 180^o	1986*
Thermal Slippings	—	$2x10^6$ rot'tns	1986*

*Space Station Technology

operate at 70° F and the other at 35° F. Single-phase pumped water circuits maintain temperature control in the modules and interface with the thermal buses outside the modules, thus avoiding the possibility of toxic ammonia gas being released in the module. The thermal buses reject unwanted heat by using an erectable centralized heat pipe radiator system (**Reference 7**).

4.5.2 Technology Trends

Thermal management technology trends are oriented to centralized thermal control whereby individual equipment can be integrated and repositioned with minimal effect on the central systems' ability to serve the remaining loads and allow for Space Station growth. Advances may provide a time-shared programmable central controller to simplify the control of heaters and thermostats and their associated control problems. High performance cold plates (1-10 W/cm^2) and distributed evaporators (multizone heat input) are needed to transport heat fluxes over greater distances than today's 3,000-12,000 W design capabilities. Lighter heat rejection radiators are envisioned as modular with on-orbit replaceable heat pipe elements (**Figure 4.5.2-1**). Mechanical refrigerators are required having a three- to five-year life with stable performance at <75 K. Solid state temperature controllers are needed to replace bi-metallic thermostats because prelaunch functional verification of the large number of thermostats required is very difficult.

Thermal control technology forecasts are provided in **Table 4.5.2-1** (**Reference 2**).

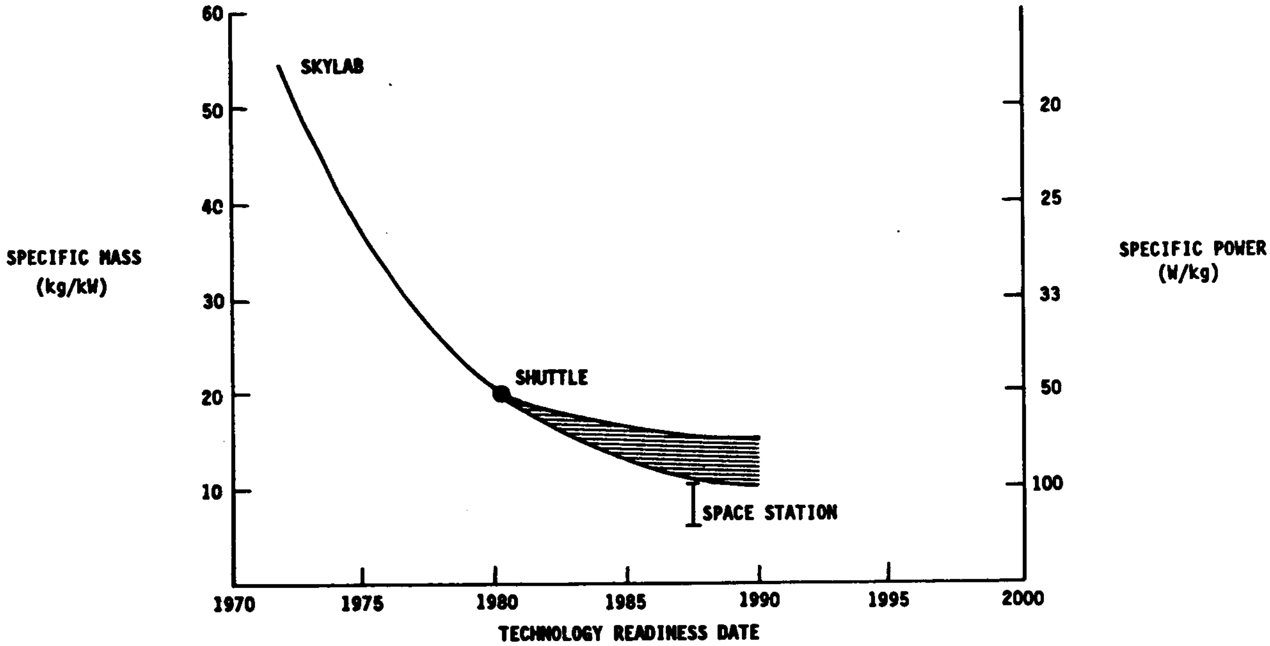


Figure 4.5.2-1 Radiator Specific Mass and Specific Power (Reference 3)

TABLE 4.5.2-1 THERMAL CONTROL TECHNOLOGY FORECASTS (REFERENCE 3)

Figure of Merit	1985	1990	1995	2000
Thermal Control Systems				
Specific Power (W/kg)	10	15	20	25
Radiators				
Specific Power (W/kg)	75	90	--	--
Heat Flux (kW/m^2)	0.5	0.7	1.0	2.0
Heat Pipes				
Thermal Transport Capacity (W-m)	1×10^4	2.5×10^5	--	--
Pumped Loop Heat Transport Systems				
Thermal Transport Capacity (W-m)	5×10^3	5×10^4	1×10^5	--
Heat Flux (W/cm^2)	10	15	30	75
Cold Plates				
Heat Flux (W/cm^2)	0.5	2.0	100	--
Passive Cryogenic Coolers				
Lifetime (yr)				
Radiators	4	7	10	12
Solids	4	5	6	7
Liquid Tanks	2	3.5	5	6
Active Cryogenic Coolers				
Lifetime (yr)				
65 K Stirling Cycle	1	4	6	7
11 K Stirling Cycle	0.25	1	3	4

C-2

4.5.3 Candidate Advanced Subsystem

The transport of Advanced Space Station hardware from Earth to low Earth orbit will be limited in size by the cargo bay of the heavy lift cargo vehicle. The largest payload size anticipated is 33 feet in diameter by 100 feet in length.

The Advanced Space Station will employ both active and passive thermal control subsystems to assure that proper operating environments are provided.

The following six candidates are active thermal control systems.

1. Pumped flow two-phased thermal buses provide controlled heat to selected Space Station locations and transport unwanted heat to externally mounted space radiators. The thermal buses will function similar to a two-phase heat pipe as shown in **Figure 4.5.3-1** but with a mechanical pump to return liquid ammonia from the space radiator end to the heat input locations (see **Reference 27** also).
2. Capillary pumped loop technology provides a high heat flux capability (up to 15 W/cm^2) to transport unwanted heat from an experiment to a thermal bus (**Reference 28**) (**Figure 4.5.3-2**).
3. Two-phased ammonia heat pipe radiator elements from 50 feet to 100 feet in length would be space-erectable to form large-area flat space radiators. Micrometeoroid or space debris damage to the radiator assembly could be repaired on-orbit by replacing the individually damaged radiator elements. Watt densities of 3.1 W/cm^2 and heat transport levels of 14 kW-

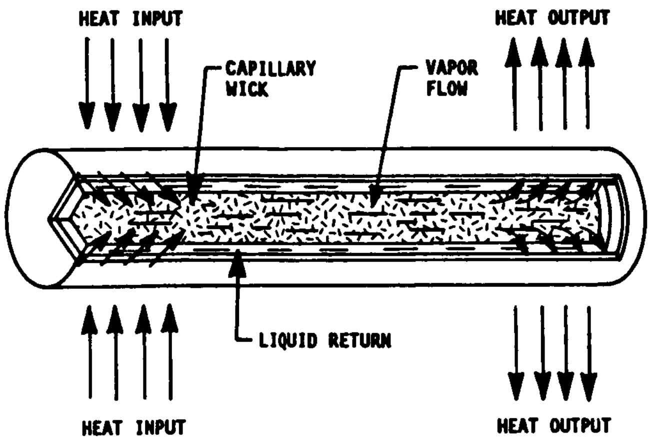


Figure 4.5.3-1 Basic Heat Pipe (Reference 3)

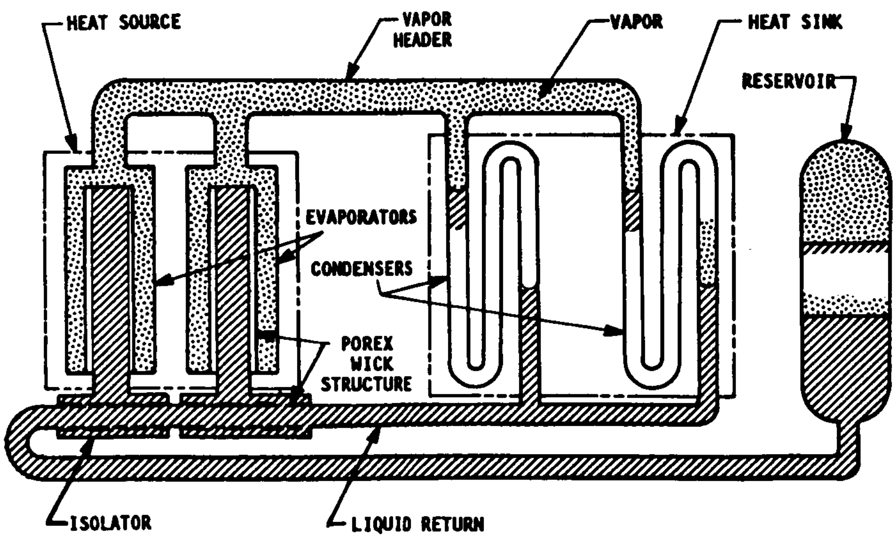


Figure 4.5.3-2 Schematic of Capillary Pumped Loop Engineering Model (Reference 28)

meters have been measured for a monogroove high-capacity heat pipe. An Advanced Trapezoidal Axial Groove heat pipe having a nominal outside diameter of 3.75 cm has a theoretical transport capacity of up to 150 kW-meters (**Reference 28**) (**Figure 4.5.3-3**).

4. Variable conductance heat pipes used with experiments mounted outside the Space Station modules can provide a variable radiator feature reducing the heater power required during cold-case operation (and non-operation) and yet allowing full, unchoked heat rejection in the hot case (**Reference 28**) (**Figure 4.5.3-4**).

5. Electronic circuit board thermal control appears feasible using a small ammonia two-phase heat pipe joined to the perimeter of the board. The heat pipe can provide thermal control to chip-size piece parts and sometimes mechanical parts (**Reference 28**) (**Figure 4.5.3-5**).

6. Liquid droplet radiators can provide high heat rejection rates using a recirculating free stream of liquid droplets (<100 um diameter) to radiate heat in space. The basic idea of the radiator concept is the large radiating surface area provided by small droplets having a minimal mass. Low vapor pressure silicone oil and molten low-fusing metal alloys are candidate radiator droplet materials selected to minimize offgassing and condensing on other Space Station surfaces. The liquid droplet radiator can be constructed much lighter

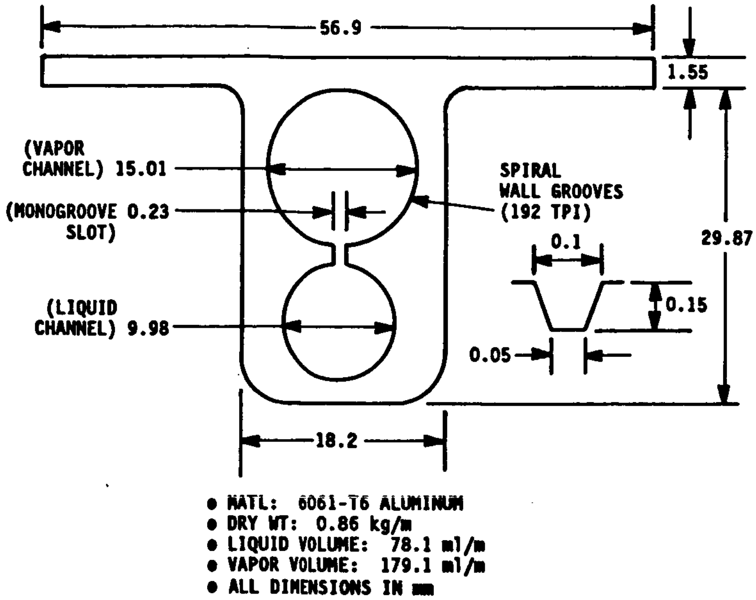


Figure 4.5.3-3 Monogroove Heat Pipe Configuration (Reference 28)

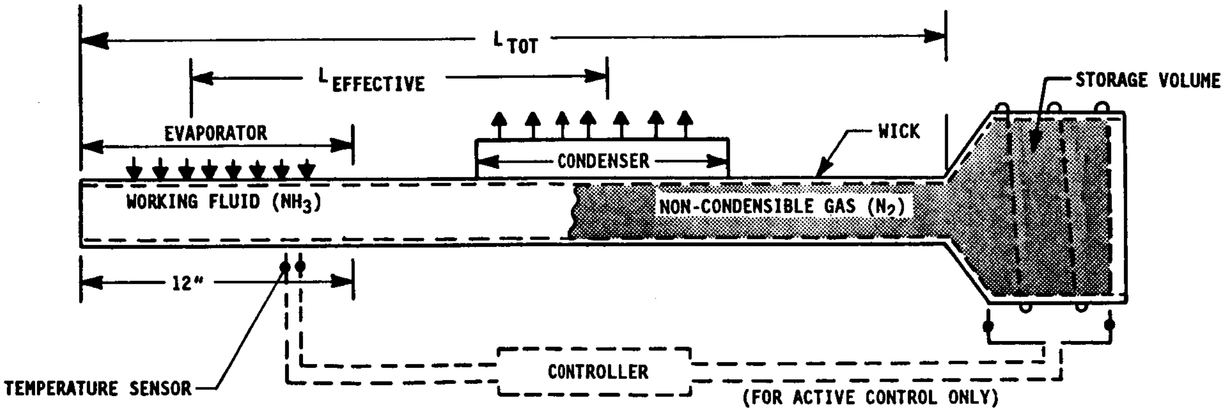


Figure 4.5.3-4 Typical Variable Conductance Heat Pipe (Reference 28)

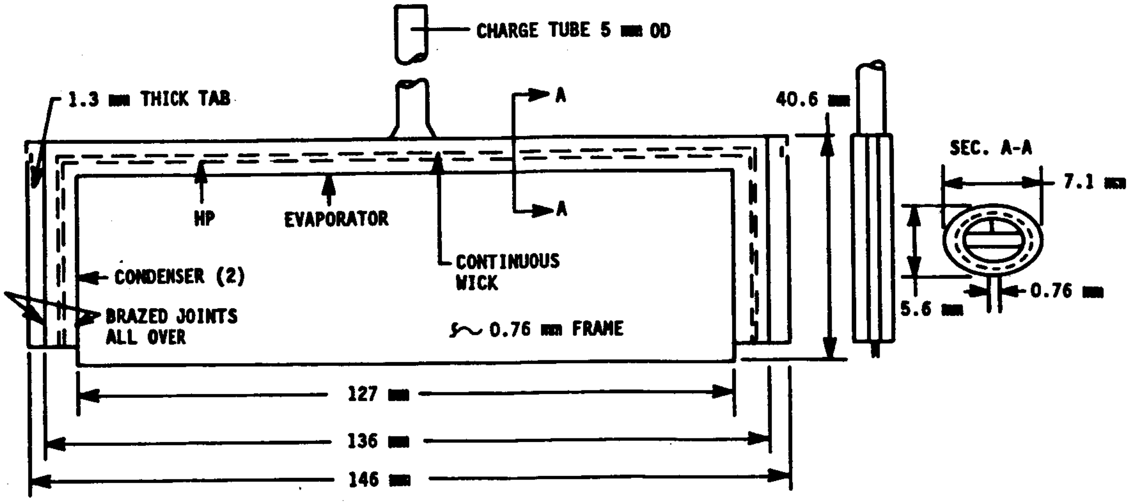


Figure 4.5.3-5 Circuit Board Heat Pipe (Reference 28)

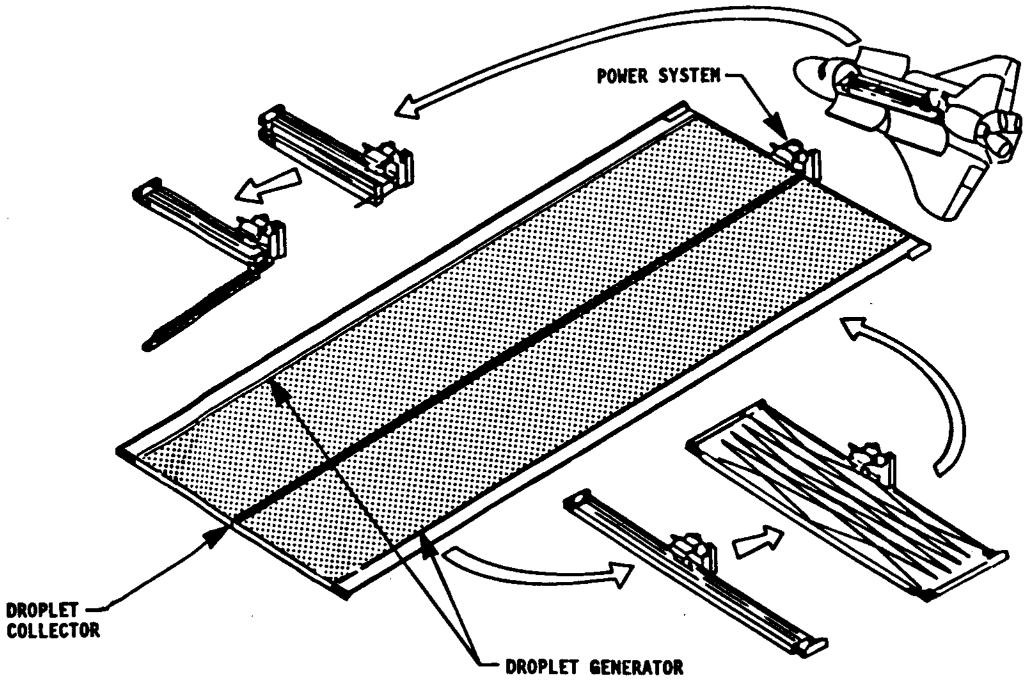


Figure 4.5.3-6 Liquid Droplet Radiator (Reference 3)

than heat pipe radiators, and the radiating area is immune to micrometeoroid damage (**Reference 3**) (**Figure 4.5.3-6**).

A liquid droplet radiator point design indicates a power to mass ratio of 4.2 kW/kg which is two orders of magnitude improvement over heat pipe radiators (**Reference 11**).

The following three candidates are passive controlled thermal systems.

1. Thermal control coatings and finishes applied to surfaces of the Space Station will provide selective reflectances or absorption of incident energy and selective emittance of self-contained heat. Contamination-resistant coatings are required to offset the effects of photolysis whereby contaminants adhere more readily to sunlit surfaces. Atomic oxygen, heat, electron fluency, and ultra-violet radiation are other degrading environmental conditions affecting the performance and life of thermal control coatings (**References 28 and 29**) (**Figure 4.5.3-7**).

2. Louvers used in combination with thermal control coatings can vary the radiating area of a surface, thereby modulating heat transfer. The louvers resemble a venetian blind being opened or closed by a thermally responsive bi-metallic spring (**Reference 28**) (**Figure 4.5.3-8**).

3. Multi-layer insulation consisting of about 25 layers of embossed and metallized plastic film interleaved with low conductance separators can provide emittance values as low as 0.005. Seams, cutouts, and attachments increase the effective emittance values (**Reference 28**) (**Figure 4.5.3-9**).

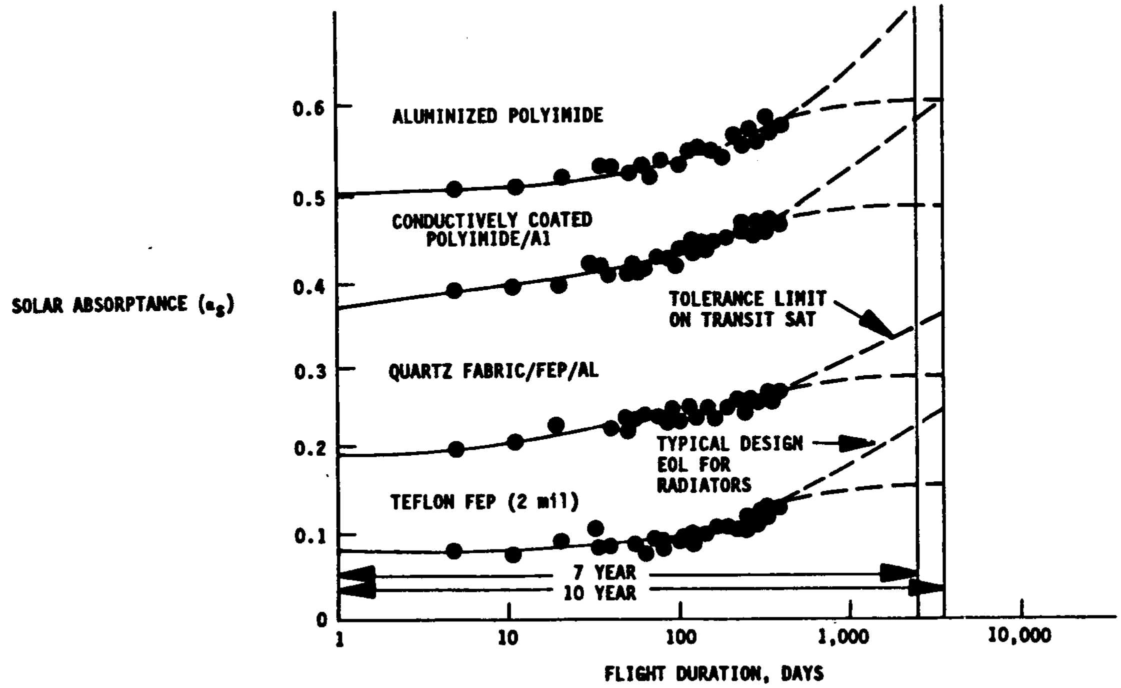


Figure 4.5.3-7 Extrapolated End-of-Life Absorptance (Reference 3)

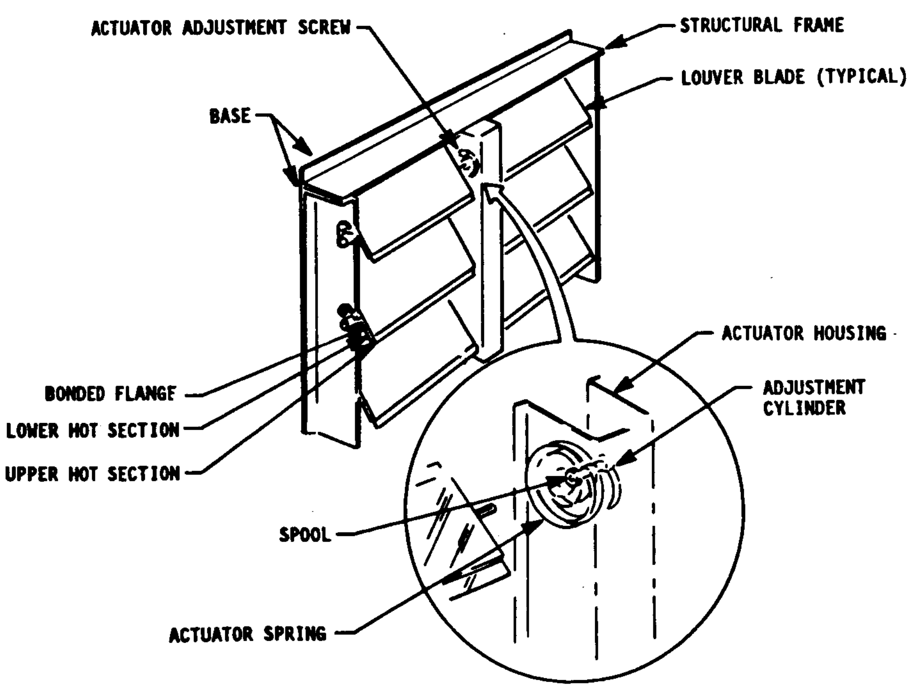


Figure 4.5.3-8 Fairchild and Northrop Louver Assembly Schematic (Reference 3)

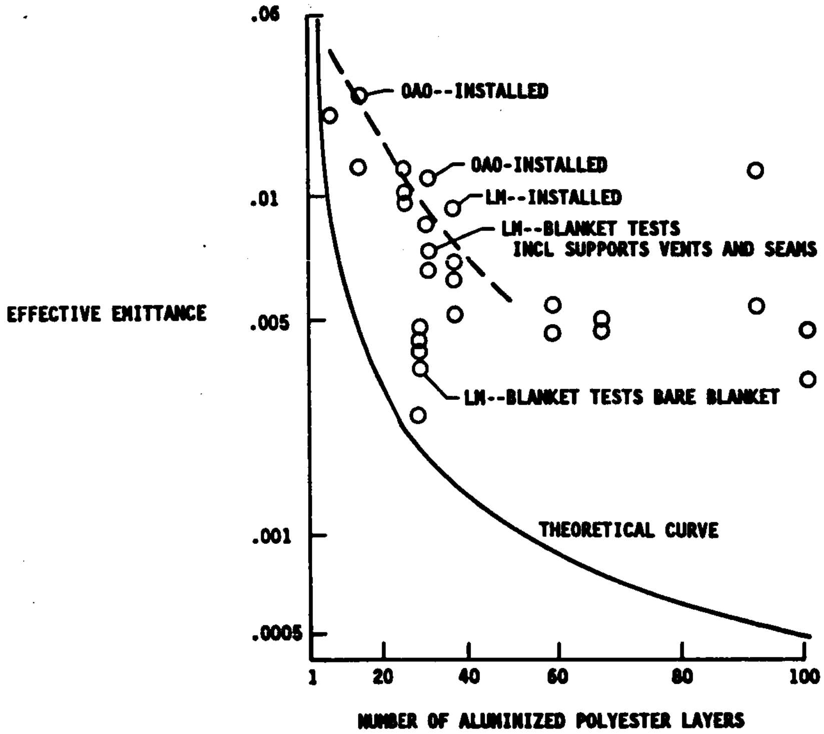


Figure 4.5.3-9 Multilayer Insulation Performance Data (Reference 3)

4.6 Environmental Control and Life Support System (ECLSS)

The functions of the ECLSS provide for:

1. Atmosphere pressure and composition control
2. Module temperature and humidity control
3. Atmosphere revitalization
4. Water management
5. Waste management
6. EVA equipment servicing
7. Fire detection and suppression

4.6.1 State-of-the-Art

The state-of-the-art in ECLSS is very similar to that of the Orbiter and Skylab. Each of the seven functions is discussed briefly with proposed changes from Orbiter and Skylab noted. In addition, **Table 4.6.1-1** summarizes the status of pertinent equipment items or options considered for application to the IOC Space Station (**Reference 21**).

1. Atmosphere Pressure and Composition Control (ACS) - The ACS system provides partial pressure control within the pressurized modules. It contains the oxygen and nitrogen storage and resupply tanks and also the distribution equipment throughout the pressurized capsules.
2. Module Temperature and Humidity Control (THC) - The THC controls cabin temperature, humidity, ventilation, and cooling where required.
3. Atmosphere Revitalization (AR) - The AR system revitalizes the cabin atmosphere. It contains hardware used to close the

TABLE 4.6.1-1 IOC SPACE STATION SUMMARY OF TECHNOLOGY STATUS FOR THE ECLSS FUNCTIONS AND EQUIPMENT

Function	Specific Equipment, Technique, or Technology	Comments or Concerns
1. Atmospheric Pressure and Composition		
a. Pressure Regulation	Aneroid Regulator	Derive from Orbiter
b. O_2 Partial Pressure	O_2 Partial Pressure Sensor	Derive from Orbiter
c. Over Pressure Control (Relief)	Relief Valves	Derive from Orbiter
d. O_2 Makeup Storage	High Pressure Tanks	Derive from Orbiter
e. N_2 Makeup Storage	High Pressure Tanks	Chemical Decomposition of N_2H_4 Alternate
2. Temperature and Humidity Control		
a. Temperature Control	Electric Heaters	Derive from Orbiter
b. Water Separation	Cold Plate Condenser with Centrifugal Separator in Modulated Bypass Loop	Derive from Orbiter
c. Humidity Control	Wick-type Humidifier in Conjunction with Heater	Derive from Orbiter
3. Atmospheric Revitalization		
a. O_2 Resupply	Water Electrolysis 3 Candidates o Solid Polymer Electrolyte o Static Feed o Water Vapor	Development for Power Efficiency in a Microgravity Environment

TABLE 4.6.1-1 IOC SPACE STATION SUMMARY OF TECHNOLOGY STATUS FOR THE ECLSS FUNCTIONS AND EQUIPMENT (Continued)

Function	Specific Equipment, Technique, or Technology	Comments or Concerns
b. CO_2 Separator	4-Element Molecular Sieve	Derive from Orbiter, Solid Amine and Electrochemical as Alternates
c. CO_2 Reduction	Bosch Process CO_2 by H_2 to H_2O and C	Sabatier Process as Alternate
d. Trace Contaminant Removal, Odor Control	3-step Process LiOH to Catalytic Oxidation Followed by Activated Carbon	Derive from Orbiter
e. Trace Gas Contaminant Monitor	GC/MS	Derive from Spacelab
f. Emergency O_2 - N_2	High Pressure Tankage	Derive from Orbiter
4. Water Recovery and Management		
a. Potable Drinking Water from Cabin Air Condensate and CO_2 Reduction	Polish to Potability in 4-step process Microbial Control, Iodine Activated Carbon Filter, Ion Exchange Bed Final Microbial Control, Iodine	Derive from Orbiter
b. Hygiene Water Recovered from Crew Wash Flush and Urine Reduction	Process through Vapor Phase Distillation	Derive from Orbiter
c. Wash Water, Recover from Dishwashing and Laundry	Semipermeable Membrane Hyperfiltration Brine Residue to Hygiene	Recovery system in Development

TABLE 4.6.1-1 IOC SPACE STATION SUMMARY OF TECHNOLOGY STATUS FOR THE ECLSS FUNCTIONS AND EQUIPMENT (Continued)

Function	Specific Equipment, Technique, or Technology	Comments or Concerns
d. Water Quality Monitor	Automated System for Continuing Measurement of Organics and Ammonia	System Being Developed
e. Crew Wash	Handwasher: as a Recirculating Air Blown Water Stream	Handwasher from Orbiter
	Shower: as Container with Recirculating Air Blown Water Stream, Hand-held Shower Head, Vacuum Water Pickup	Adapted from Sky Lab
f. Dishwash	No System Defined	Development Required
g. Clothes Wash	No System Defined	Development Required
5. Waste Management		
a. Urine Collection and Treatment	Air Transported from Urinal Pretreat to Stabilize Ammonia from Urea and Control Bacteria	Derive from Orbiter
	Waste Water Processes through 3 Options for Distillation o Vapor Compression o Thermoelectric Integrated Membrane (TIMES) o Vacuum Distillation Pyrolysis o Flash Evaporation o Wick Evaporation	Options in Development TIMES Present Choice

TABLE 4.6.1-1 IOC SPACE STATION SUMMARY OF TECHNOLOGY STATUS FOR THE ECLSS FUNCTIONS AND EQUIPMENT (Concluded)

Function	Specific Equipment, Technique, or Technology	Comments or Concerns
b. Feces Collection and Treatment (Feces Dried and Stored)	Combined Air Flow & Centrifugal Separator, Collector Bag for Return to Earth	Derive from Orbiter, and Skylab
c. Trash Compactor	Mechanical Compaction for Storage and Return to Earth	No Configuration Defined, Development Item
6. Fire Detection and Suppression		
a. Fire Detection	Smoke Alarms	Derive from Household System
b. Fire Suppression Extinction	CO_2 Suppressant and Vent o Hand CO_2 Units o Pressurized System Manifolded to Racks and Bays	Derive from Orbiter

crew's oxygen loop and is a departure from Orbiter/Skylab. Water is electrolyzed to provide metabolic oxygen. The by-product hydrogen is used in a CO_2 reduction process to yield water and reaction by-products. The water is used to replenish the crew's potable water supply, and the carbon by-product is returned to Earth. The carbon dioxide produced by the crew is routed to the CO_2 reduction unit.

4. Water Recovery and Management - Water recovery and reuse is a departure from Orbiter/Skylab. Water reclaimed from hygiene and urine is recovered for use for hygiene purposes. Reclaimed water is electrolyzed in order to resupply the metabolic oxygen, and the reclaimed condensate is the primary source of the crew's potable water supply (along with the CO_2 reduction water output).

5. Waste Management - Waste management consists of collecting the urine waste water and collecting and processing the fecal and trash waste. Use of the urine waste water has been mentioned above. Fecal waste is vacuum dried, bagged, and returned to the ground. Trash is collected and also returned to the ground.

6. EVA Equipment Services - The ECLSS system provides fluid services to the EMU and MMU.

7. Fire Detection and Suppression - This subsystem consists of hardware to detect and suppress fires in pressurized volumes. The technology is similar to that of the Orbiter/Spacelab.

Figure 4.6.1-1 is a schematic drawing of the partially closed ECLSS. The ECLSS is sized to accommodate the design loads of **Tables 4.6.1-2** and **4.6.1-3.**

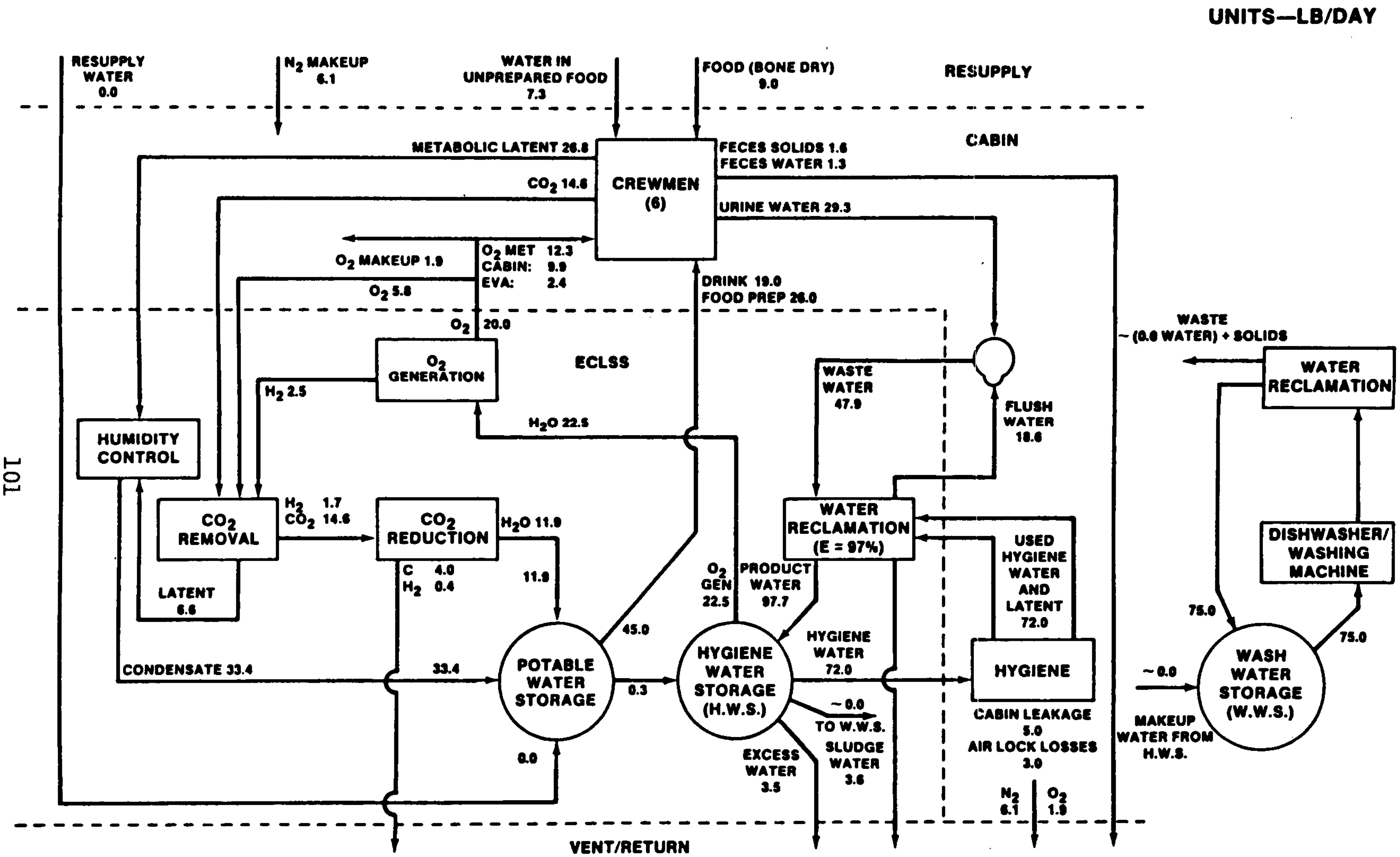
Numerous studies have been made to examine methods for performing some or all of the ECLSS functions, some experimental studies, and many analytical studies (see **References 30 through 33**, for example). It should be noted that experimental studies have been made under Earth "g" conditions. There appear to be no readily available results from tests at zero or reduced "g" conditions, which could be important in some of the life support functions.

4.6.2 Technology Trends

There are two major trends in the ECLSS. One is to improve the overall recovery of metabolic oxygen and potable water by proper selection of the processes for these purposes and also to examine relative costs (**Reference 30**, for example). The other trend is to make use of synergistic relationships between the ECLSS and other subsystems. The two trends are discussed in some detail in Sections 4.4.3 and 5.2

4.6.3 Candidate Advanced Subsystem

Life support functions on-board an Advanced Technology Space Station will have to perform at levels that accommodate the particular crew complement. The configuration definition studies that led to the concept described below in Section 6 recognized that gravity would eliminate some of the design complexities imposed upon the IOC equipment. The concepts for synergy in the generation of O_2 and H_2 for both life support and fuel impact



(Note: Numbers are in pounds per day and apply to a 6-man crew.)

Figure 4.6.1-1 Space Station ECLSS Architecture (Reference 6)

TABLE 4.6.1-2 ECLSS DESIGN LOADS (REFERENCE 7)

General:	
Number of Crew	8.00
Resupply Interval (days)	90.00
THC Subsystem:	
Sweat and Respiration H_2O (lbm/man-day)	4.02
Metabolic and Sensible Heat (Btu/man-day)	11,200.00
Hygiene Latent H_2O (lbm/man-day)	(TBD)
Food Prep. Latent H_2O (lbm/man-day)	(TBD)
Laundry Latent H_2O (lbm/man-day)	(TBD)
Freezer Internal Vol. per Module (ft3)	(TBD)
Refrigerator Internal Vol. per Module (ft3)	(TBD)
Freezer Load per Module (Watts)	(TBD)
Refrigerator Load per Module (Watts)	(TBD)
Dish Wash Latent H_2O (lbm/man-day)	0.06
ACS System:	
Total IOC Station Atmosphere Leakage (lbm/day)	5.00
Air Lock Gas Loss	(10% of Leakage gas/operation)
U.S. Module Volume (ft3)	6,166.00
AR Subsystem:	
Metabolic O_2 (lbm/man-day)	1.84
Metabolic CO_2 (lbm/man-day)	2.20
FDS Subsystem:	
(TBD)	
WRM Subsystem:	
Potable H_2O, Drinking (lbm/man-day)	4.09
Food Preparation H_2O (lbm/man-day)	1.58
Metabolic H_2O (lbm/man-day)	0.76
Clothes Wash H_2O (lbm/man-day)	27.50
Dish Wash H_2O (lbm/man-day)	12.00
Hand Wash H_2O (lbm/man-day)	4.00
Shower H_2O (lbm/man-day)	8.00
Urinal Flush H_2O (lbm/man-day)	1.09
Urine H_2O (lbm/man-day)	3.31
Food H_2O (lbm/man-day)	1.10
Hygiene Latent H_2O (lbm/man-day)	0.96

Table 4.6.1-2 ECLSS DESIGN LOADS (Concluded)

WM Subsystem:	
Food Packing (lbm/man-day)	1.00
Urine Solids (lbm/man-day)	0.13
Fecal Solids (lbm/man-day)	0.07
Sweat Solids (lbm/man-day)	0.04
Wash H_2O Solids (percent)	0.44
Shower/Hand Wash H_2O Solids (percent)	0.12
Trash (lbm/man-day)	1.00
Trash Volume (ft3/man-day)	0.10
Fecal H_2O (lbm/man-day)	0.20
EMU Condensate (lbm/man-hr)	(TBD)
ES Subsystem:	
EVA O_2 (lbm/man-hr)	0.18
EVA CO_2 (lbm/man-hr)	0.22
EVA H_2O (lbm/man-hr)	(TBD)
EMU Condensate (lbm/man-hr)	(TBD)

TABLE 4.6.1-3 ATMOSPHERE AND WATER REQUIREMENTS (REFERENCE 7)

Parameter	Units	Operational	90-day Degraded (1)	28-day Emergency
CO_2 Partial P	mmHg	3.0 max	7.6 max	12 max
Temperature	deg F	65-80	60-85	60-90
Dew Point (2)	deg F	40-60	35-70	35-70
Potable Water	lb/man-day	6.26-11.35	6.26 (3)	6.26 (3)
Hygiene Water	lb/man-day	12 (3)	12 (3)	0
Wash Water	lb/man-day	28 (3)	0	0
Ventilation	ft/min	15-40	10-100	5-200
O_2 Partial Pressure (4)	psia	2.83-3.35	2.4-3.45	2.3-3.45
Total Press (5)	psia	14.5-14.9 (9)	14.5-14.9	14.5-14.9
Dilute Gas	—	N_2	N_2	N_2
Trace Contam (8)	mg/m^3	TBD	TBD	TBD
Microorganisms	CFU/m^3 (6)	1000 (7)	1000 (7)	1000 (7)

NOTES:

(1) Degraded levels meet "Fail Operational" criteria.
(2) Relative humidity shall be within the range of 25-76 percent.
(3) Minimum
(4) In no cases shall the O_2 partial pressure be below 2.3 psia, or the O_2 concentration exceed 23.8% of the total pressure.
(5) All ECLSS subsystems shall be compatible with 14.7 psia total pressure.
(6) CFU - Colony Forming Units
(7) These values reflect a limited base. No widely sanctioned standards are available.
(8) Based on NHB 8060.1B (J8400003).
(9) Hyperbaric chamber pressure shall be TBD psia minimum.

the design of equipment. In such a context, four areas of technology appear to offer particular benefits pertinent to life support functions. These are summarized in the following four sections.

4.6.3.1 Semipermeable Membrane Development for Gas Separations

Semipermeable membranes are well established and provide the basis for hyperfiltration and the molecular sieves used to separate CO_2 from the cabin air. Developments in membrane technology are continuing for medical applications (renal dialysis, oxygen permeable contact lenses, etc.) and gas constituent separations. Microgravity processing appears as a potential means for producing extra-thin films with controllable and uniform porosity. These developments would lead to a straightforward separation system as a series of membrane filters, each rejecting (or selectively passing) a particular molecular constituent.

4.6.3.2 Wet Air Oxidation for Water Reclamation

Oxidation of carbonaceous materials in a water solution is a recognized method for disposal of such wastes. The process has been developed, applied commercially, and studied for application to flight equipment. In the context of synergism, wet air oxidation is a recommended development effort. The potential benefits together with a mass balance estimate appear below in Section 5, System Synergies.

4.6.3.3 Electrolytic Cells for Generation of O_2 and H_2 in Quantity

The recommendations from the propulsion system indicated a shared effort for the development of electrolysis cells. The IOC definition identified three options under development; all were specifically configured to operate in a microgravity environment (**Reference 21**). The recommended development for the Advanced Technology Space Station becomes an electrically efficient cell which can operate over the widest practical range of current densities to provide O_2 and H_2 in response to fluctuations in the on-board electrical power demand (e.g., the cells make the Space Station appear as a constant current load for the generators).

4.6.3.4 Synergistic Utilization of the Carbon from CO_2 Reduction

An increase in crew size coupled with wet air oxidation of organic wastes will yield a significant amount of elemental carbon from the Bosch process for CO_2 reduction. In the process of reductions, amorphous carbon is deposited on the iron catalyst in a form that presently has no identified utilization. A utilization synergy into activated carbon, graphite, or other appropriate forms would benefit the operation. High temperature processing could be achieved by utilizing a portion of the solar beam concentrations which drive the electrical power generators.

4.7 Extravehicular Activity (EVA) Subsystem

EVA is the term used to describe activities performed by the astronauts outside of the pressurized spacecraft environment. The two general classes of EVA are:

1. Planned EVA, which are tasks included in a normal mission time line that perform such functions as erection of Space Station components, assembly of spacecraft components, and repair of satellites.

2. Unscheduled EVA, which are tasks which were not planned for the normal mission time line but might be required for repair or replacement of failed components to enhance mission success.

In general, EVA is provided for assembly, maintenance, servicing, and repair of the Space Station and any other large space structures; servicing and repair of satellites; maintenance servicing and repair of the Orbiting Maneuvering Vehicles (OMV) and Orbital Transfer Vehicles (OTV); and maintenance, servicing, and repair of payloads and experiments.

4.7.1 State-of-the-Art

The current state-of-the-art in EVA is that existing for the Space Shuttle flights. The EVA systems include the Extravehicular Mobility Units (EMU) and the Manned Maneuvering Units (MMU). The EMU's are independent anthropomorphic (body-shaped) systems that provide environmental protection, mobility, life support, and communications for the crewmen (**Figure 4.7.1-1**). The units have no propulsion and generally are tethered. The basic components of the EMU consist of a space suit that includes the pressure garment, a primary life support system (PLSS), and an ultra-high frequency radio communications system. The EMU operates with a pure oxygen atmosphere at 4.3 pounds per square inch, and the units weigh about 250 pounds. The characteristics of the EMU's are shown in **Table 4.7.1-1**. A complete description of the current (Shuttle) EMU is given in **Reference 34.**

The MMU's are self-contained propulsive backpacks (**Figure 4.7.1-2**) designed to increase mobility in EVA. An MMU is fastened to the EMU and can be put on or taken off by one unassisted crew member. **Figure 4.7.1-3** shows

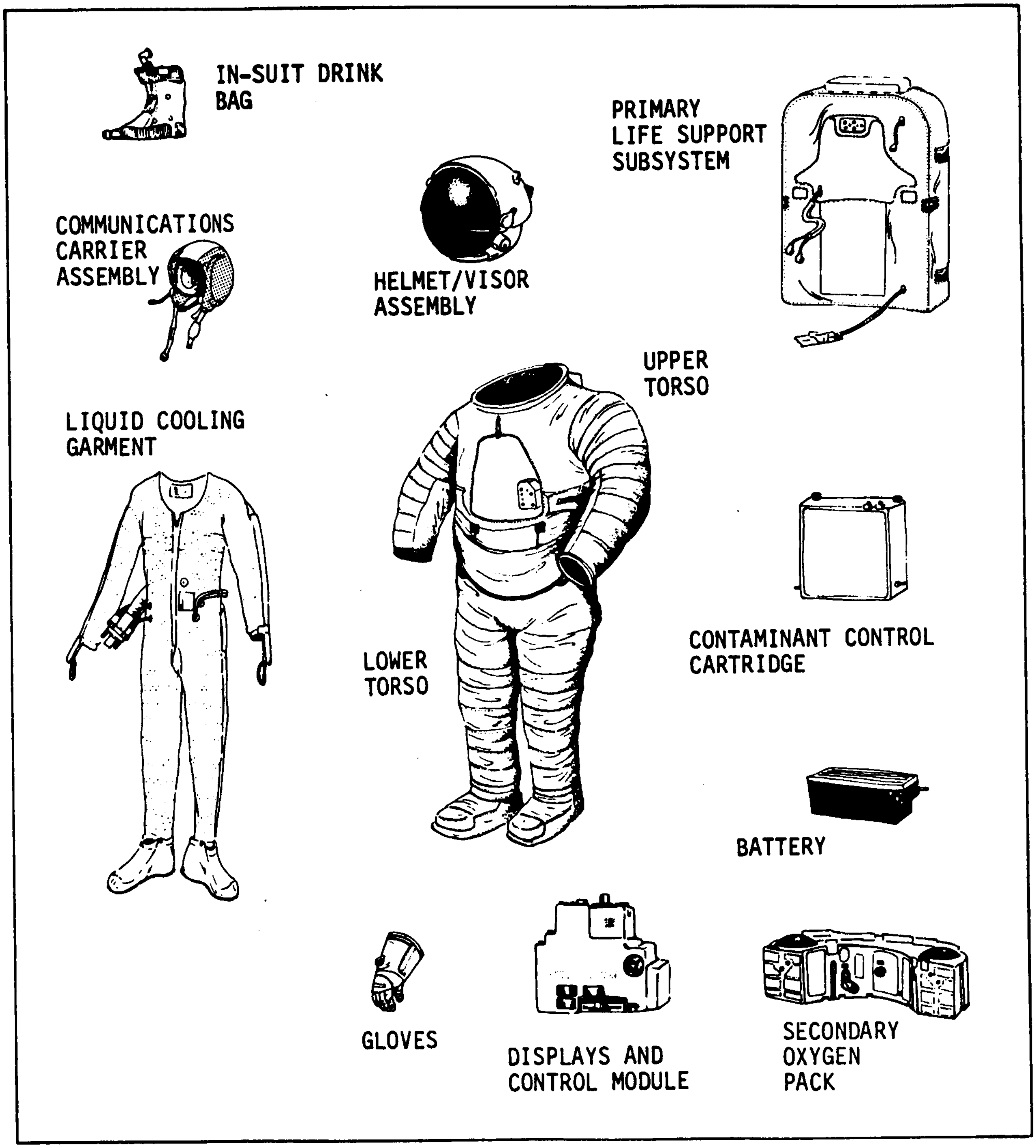


Figure 4.7.1-1 Extravehicular Mobility Unit Components (Reference 34)

TABLE 4.7.1-1 CHARACTERISTICS OF THE EVA SUBSYSTEM (REFERENCE 34)

Extravehicular Mobility Unit	
Weight	250 pounds
Atmosphere	O_2, 4.3 psi minimum
Capability	8 hours per day at an average of 1000 btu per hour
Manned Maneuvering Unit	
Weight	325 pounds
Propellant	GN_2
Total Impulse	1392 pound-seconds
Max Range	3000 feet
Electrical Power	752 watt-hours (2 batteries)

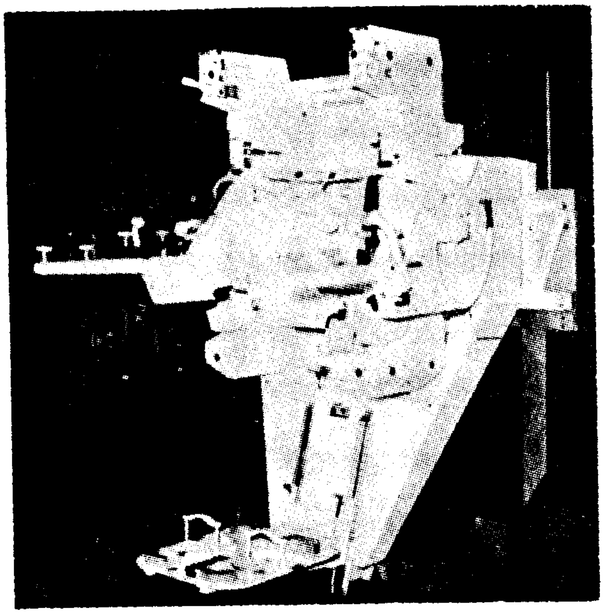


Figure 4.7.1-2 Manned Maneuvering Unit (Reference 34)

Figure 4.7.1-3 Astronaut in EMU and MMU (Reference 34)

a crewman in an EMU with a MMU attached. The MMU has complete six-degree-of-freedom control authority with spacecraft-type piloting logic. It can perform translational or rotational maneuvers about each axis individually or in any combination. Control inputs are made through use of hand controllers. The left-hand controller is used for translational maneuvers, and the right-hand controller is used for rotational maneuvers. The MMU also can perform attitude-hold on command. Some of the physical characteristics of the MMU's are given in **Table 4.7.1-1.** Additional details relative to the MMU's are given in **Reference 34.**

4.7.2 Technology Trends

Technology trends have been aimed at EMU improvements, such as increased suit mobility, improved cooling, improved communications, etc. Development work has advanced the design of a space suit that would operate at a higher internal pressure than the current 4.3 psi. The objective has been a reduction in the amount of time required for pressurizing and depressurizing before and after EVA (**Figure 4.7.2-1**, taken from **Reference** 35), and has provided a more normal gas atmosphere. The accumulative physiological effects of many cycles of pressurizing and operating in a low pressure oxygen atmosphere are not fully understood (**Reference** 35).

MMU improvements have been concerned primarily with increasing the amount of nitrogen propellant.

EVA has been very successful, as demonstrated in the Skylab and Shuttle missions. However, there has been a growing concern relative to the extended EVA time and effort projected for the assembly and maintenance of a Space Station (**References 36 and 37**, for example). This has given an

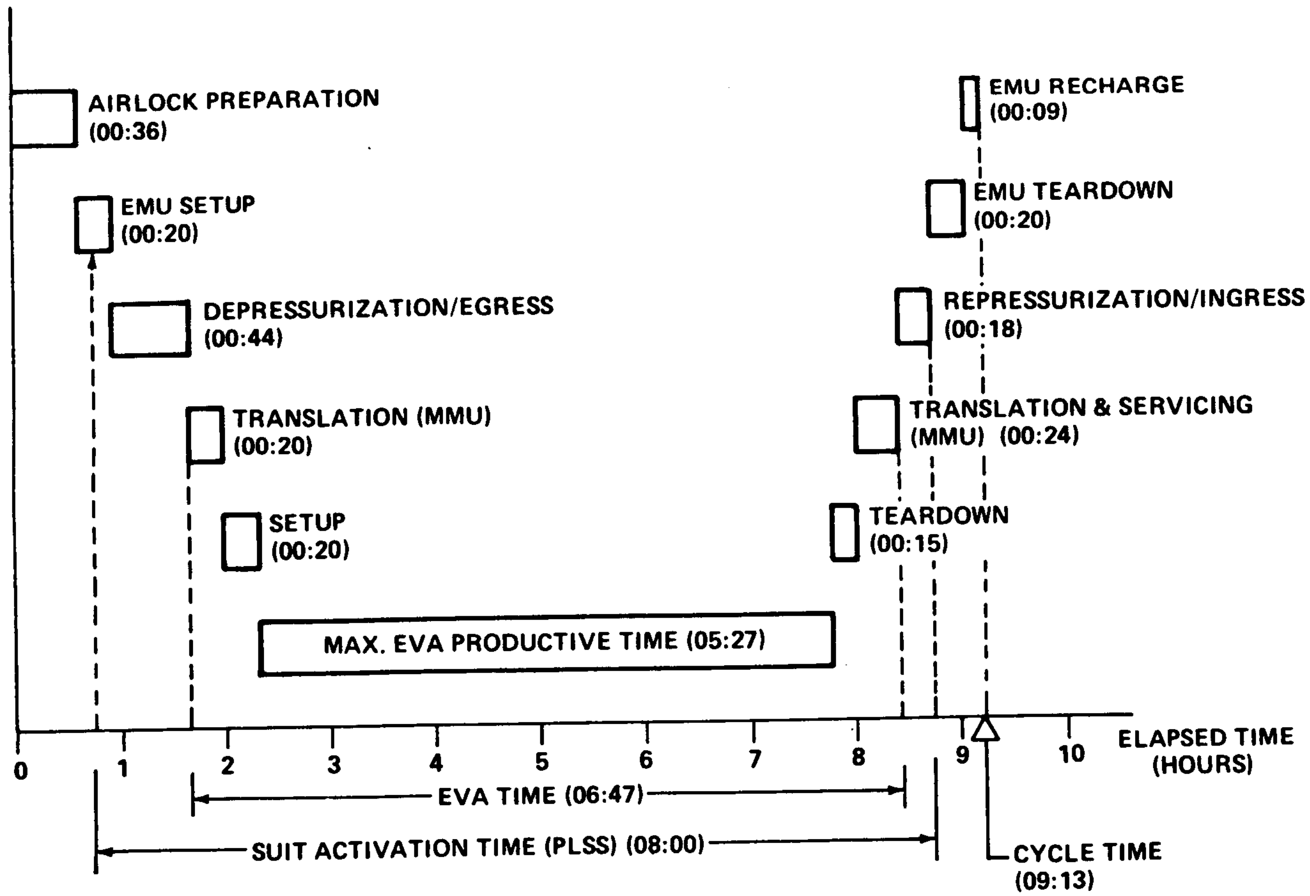


Figure 4.7.2-1 EVA Cycle Time (Reference 35)

additional impetus to the concepts of using mechanical devices in place of EVA and using astronauts as a backup when necessary. The mechanical devices being examined have taken many forms, as shown in **Figures 4.7.2-2** and **4.7.2-3** from **Reference 38.** The degree of automation has been from intelligent robots to teleoperators and extends to a crewman in an enclosure manipulating robotic arms. The area of robotics is receiving considerable attention. (See **Reference 39**, for example.)

4.7.3 Candidate Advanced Subsystem

If technology continues to advance at its current rate, it would appear that "intelligent" robots could be developed for the time period of interest and that they would be used in place of EVA. The future use of robotics for Space Station is likely to be through integration of efforts to design tools, to tailor assembly procedures, and to develop repair procedures for use of robots.

4.8 Communications and Tracking Subsystem

The Space Station communications and tracking subsystem performs the critical functions that provide the internal on-board audio and visual channels, provides all of the external radio frequency links, and tracks the positions of all the free flyers plus the rendezvous support for docking the Shuttle. Each of these functions employs equipment and techniques that are within the capabilities of established technology. Support for future missions envisions an expansion of communications system capabilities to levels which exceed the present limits of technology. Configurations for future Space Stations must address communications support at carrier

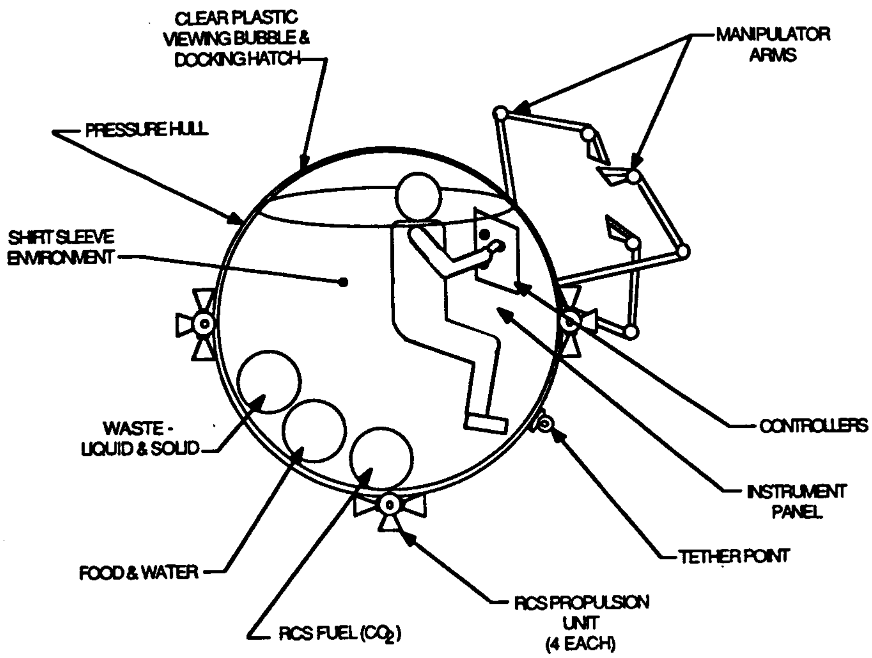


Figure 4.7.2-2 EVA Bubble Concept (Reference 38)

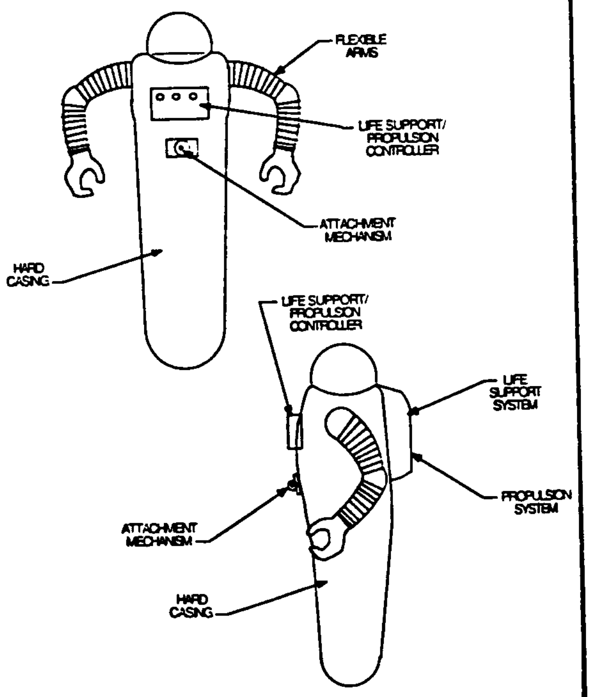


Figure 4.7.2-3 EVA Hard Suit Concept (Reference 38)

frequencies which may not be compatible with transmission through the atmosphere of the Earth; **Figure 4.8-1** illustrates some of the concerns. Within the presently used portion of the microwave spectrum, water absorption, particularly from rainstorms, impacts Earth transmission within the K band; multiple beams and extra power become necessary. Extension of the operating frequency upward faces the oxygen absorption peak in the vicinity of 60 GHz and an ever-increasing absorption by water. Throughout the world, utilization of microwaves will continue to increase over that portion of the spectrum from K band and below. Therefore, carrier frequency assignments and transmission priorities will become more important considerations as the open-to-Earth portion of the microwave spectrum saturates from the total world demand. These considerations are addressed in the descriptions of communications and tracking system technology.

4.8.1 State-of-the-Art

4.8.1.1 Space Station On-board Systems' Capabilities

The pertinent performance capabilities for the radio frequency links installed on-board the IOC Space Station are summarized in **Table 4.8.1-1** for the communication elements and in **Table 4.8.1-2** for the tracking elements. The principal data handling and communication links operate with the TDRSS for transmissions to Earth. As presently configured, all communications to and from the Earth pass through the TDRSS such that the Space Station's capabilities reflect the system limits within the TDRSS. Uprating of the Earth's data links for the Space Station envisions a new generation of relay satellites with data rates in the Gigabit per second range. The other

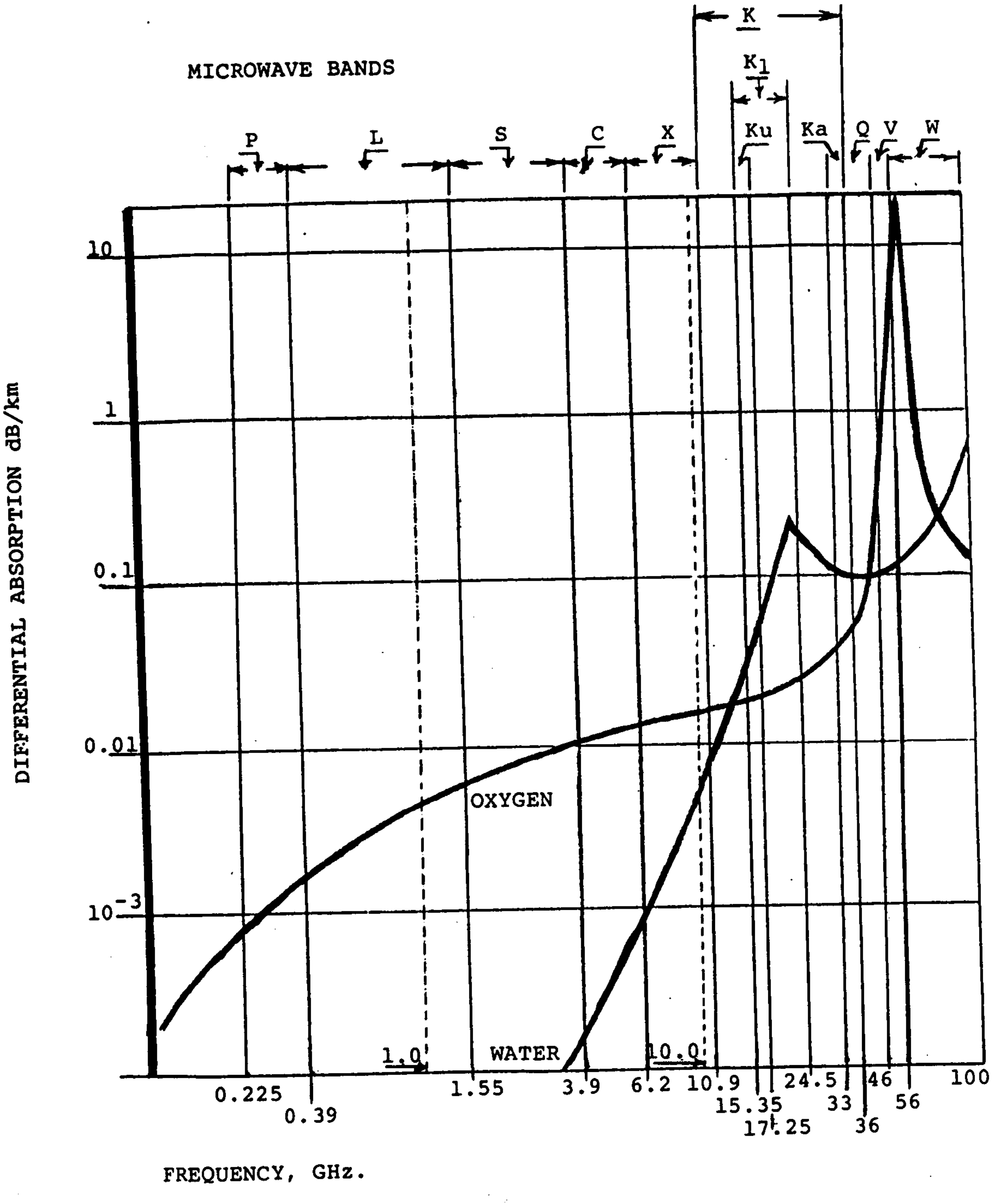


Figure 4.8-1 Atmospheric Absorption for Microwaves (Extracted from Reference Data for Radio Engineers, Howard W. Sams and Co., Inc., Indianapolis, IN, 1979)

TABLE 4.8.1-1. COMMUNICATION LINK CHARACTERISTICS RELATIVE TO THE SPACE STATION (REFERENCE 6)

VEHICLE LINKS	CAPABILITIES		DATA RATE (MAX)		NO. OF VEHICLES (SIMULTANEOUS)	RANGE (MAX) (NMI)	COMMENTS
	XMIT	RCV	XMIT	RCV			
SS-TDRS AT KuBAND	VOICE, TLM TV, DATA	VOICE, CMD TV, DATA TEXT & GRAPICS	300-MBPS	25 MBPS	ONE	23,000	SINGLE ACCESS - TDRS COMPATIBLE
S-BAND	VOICE,TLM	VOICE,CMD	3 MBPS	300 KBPS	ONE	23,000	SINGLE ACCESS - TDRS COMPATIBLE
S-BAND	TLM	CMD	96 KBPS	32 KBPS	ONE	23,000	REDUCED DATA RATE DURING ASSEMBLY PHASE
SS-ORBITER S-BAND	TLM	CMD	16 KBPS	2 KBPS	ONE	20	ORBITER COMPATIBLE
K-BAND	VOICE	VOICE	16 KBPS	16 KBPS	ONE	20	UPGRADED ORBITER EVA SYSTEM
SS-EVA/MMU K-BAND	VOICE,CMD	VOICE,TLM	48 KBPS	64 KBPS	TWO	0.54	PROX. OPS. MULTI-ACCESS SYSTEM
	TV		400 KBPS				FREEZE-FRAME TV
K-BAND	–	TV		25 MBPS	TWO	0.54	PROX. OPS HI-DATA-RATE SYS STANDARD TV
SS-FREE FLYER PLATFORM K-BAND	CMD	TLM	48 KBPS	64 KBPS	ONE GROW TO EIGHT	1080	FAR-RANGE LOW-DATA-RATE SYS
K-BAND	–	TV OR DATA	–	5 MBPS GROW TO 25 MBPS	ONE GROW TO EIGHT	1080	FAR-RANGE HI-DATA-SYS CO-ORBITAL
SS-OMV K-BAND	CMD	TLM	48 KBPS	64 KBPS	ONE	20	PROX. OPS MULTI-ACCESS STS.
S-BAND	–	TV	–	25 MBPS	ONE	0.54	PROX. OPS. HI-DATA-RATE SYS. STANDARD TV
SS(MRMS)-ORBITER S-BAND	TLM	CMD	16 KBPS	2 KBPS	ONE	0.05	ORBITER COMPATIBLE
	TV		(4.5 MHZ)				
SS-MRMS S-BAND	CMD	TLM	2 KBPS	16 KBPS	ONE	0.05	MRMS DEDICATED RF SYS
		TV		(4.5 MHZ)			

TABLE 4.8.1-2 SPACE STATION TRACKING LINK CHARACTERISTICS (REFERENCE 6)

VEHICLE LINKS	CAPABILITIES	FREQ.	DATA RATE	# OF VEH.	RANGE	COMMENTS
SS-ORB SS-OMV	RANGE RANGE-RATE AZIMUTH ELEVATION ANGLE RATE	Ku BAND	1/SEC DURING TRACK	ONE	20 NMI.	
SS-PLATFORM SS-FREE-FLYER	GPS NAV POSITION DATA ON COMM LINK	K BAND	1/10 SEC	EIGHT	1080 NMI.	GPS RCVR REQ'D ON EACH VEH.
SS-EVA	GPS POSITION ON COMM LINK	K BAND	1/SEC	TWO	3280 FT	GPS RCVR ON EACH MMU
SS-GPS	NAV POSITION DATA	L BAND	1/10 SEC	FOUR NAV-STAR	N/A	
SS-DOCKING VEHICLES	RANGE RANGE-RATE AZIMUTH ELEVATION ATTITUDE	OPTICAL	1/SEC	ONE	1000 FT	ONE FOR EACH DOCKING PORT

communications links address the on-orbit support functions. The links to the Orbiter support the resupply and fueling. The links for EVA and MRMS reflect on-board support activities. The Space Station support to deployment of free fliers appears in the OMV and platform links. The support to free flyer platforms envisions growth up to eight units with a communications link extending line-of-sight to the horizon at the nominal Space Station altitude.

The tracking capabilities support the operations within horizon line-of-sight to the Station. The capabilities listed reflect the particular requirements associated with rendezvous and docking. The types of data and measurements presented increase at close range to provide the necessary monitor for berthing and engagements. The communications system within the Space Station provides for voice and high resolution video in addition to the data transmissions. The on-board communications utilize digital techniques for transmission to permit recording and down-linking to Earth. A limited number of audio channels include on-board encryption to permit secure or private communications.

4.8.1.2 Space Station Communications Technology Status

An assessment of the operations for the Space Station in LEO provides a means for estimating the status of pertinent communications technologies. Practical considerations dictate that earth communications links must pass through a relay satellite in GEO. Operations as a communications relay station must recognize the effects of Earth orbit and the changing solar position throughout an orbit. In such a context, the principal limit imposed by technology appears as the attainable transmitted bit rate and the acceptable bit error rate. These features in turn become defined in terms of operating frequency, transmitter powers, and antenna considerations. The identified status of technology for data transmissions to earth appears in summary as the capabilities planned or under development for the tracking and data acquisition satellite (TDAS) which represents the next generation replacement for the TDRSS (which is now moving into orbital operation). The principal features of the TDAS include:

1. Data Rate - Data will transmit at an average rate of 250 Mbps and employ up to 12 channels in each spacecraft. The carrier will operate in the 33 to 36 GHz range (Ka band) and have simultaneous transmissions to a number of ground stations (to overcome atmospheric effects such as rain). The channels will have burst rate capabilities up to 1,200 Mbps.
2. Bit Error Rate - Nominal bit error rates will be one error in 10^5 to 10^6 bits. Coding techniques will extend the accuracy for special cases.
3. Antenna - The down link will employ a 3-meter dish capable of transmitting nine simultaneous beams (5 fixed and 4 adaptable, each scanning 1 by 2 degrees). The antenna will be configured for a focal-length-to-diameter ratio of 0.45 and require a surface accuracy of 0.25 mm (0.01 inch).

4.8.2 Technology Trends

Continuing advancement for each of the system elements summarizes the NASA developmental approach and trends for communications technology. The present development and research efforts focus upon specific improvements in the performance of individual elements that lead to higher data rates, improved data accuracy, extending the operating frequency spectrum, and expanding the distances for transmission links.

4.8.2.1 Antenna Developments

The trends for antennas address multiple beams, size, and beam control as geometric accuracy and phased-array techniques. The needs for multiple frequency (multichannel) operation respond to the requirement for ever-increasing data rate transmission to Earth; multichannel operation provides the necessary option. The replacement for the TDRSS envisions nine channels through one 3-meter antenna (**Reference 3**). Other systems propose more than 100 channels into a large (up to 55-meter) antenna. Multibeam operation shows no upper theoretical limit; however, practicalities in terms of aperture blockage due to feed elements and related structure will set the real upper limit and become characteristic for a particular unit or installation. Developments in the elements which feed an antenna address reduction in size of interfering materials as well as the electromagnetic properties of those materials.

The geometric requirements for beam control relate the surface aberrations to the wavelength transmitted; typically, the surface contour must conform to the theoretical geometric shape (parabola, etc.) with tolerances less than three percent of the wavelength. Antenna development efforts address the structural implications in terms of stable materials, fabrication techniques, and erection or deployment methods. Developments in antenna geometric capabilities will continue in step with mission requirements. Controls over beam direction can be accomplished within the feed system either directly (as an off-axis feed) covering a few degrees or by relative phase control of the individual feeds into a mosaic of small antenna elements (a phased-array). Phased-array antennas are included in present advanced mission concepts. The technology has been well established for radar (centimeter) microwave applications (e.g., the U. S. Navy Aegis Class Cruisers). The extensions involve the development of power dividers and phasing controls for operation in the millimeter wavelength range.

4.8.2.2 RF Switching

Transmit/receive operations with multibeam antennas imply high speed matrix-type switching in the RF portion of the system. The TDAS follow-on to the TDRSS anticipates switching nine channels into 30 to 35 transmit/receive options accomplished in nanoseconds. These requirements build on existing equipment and address material selections or construction techniques as used for monolithic microelectronics. The present developments are building on the GaAs semiconductor system to provide the electrical conductivity and the use of field-effect transistors to obtain the speed and control. GaAs has shown the capability to operate in the picosecond regime in some configurations. Ferrites appear as the alternate material which can support RF switching applications. The development of ferrite switches has proceeded to the point of demonstrating performance in the 32 to 37 GHz frequency range with low losses (0.25 db) and switching accomplished in less than 20 microseconds.

4.8.2.3 Transmitters and Amplifiers

Output power stands as the criterion for the elements which produce a modulated communication channel as a feed to an antenna. The output power provides the signal strength against the background noise which effectively defines distance for transmission and data quality. Developmental efforts pursue three separate approaches to these elements in terms of solid state transmitters, electron beam units, and coupled cavities. Each shows particular benefits against disadvantages. The solid state units focus upon the application of the GaAs system and take advantage of its inherent speed, power efficiency, stability, and reliability. The developments recognize the inherent power limit of individual devices and address the combination of outputs to attain the needed power level. Combinations which can deliver up to 40 watts have been operated in the laboratory, and efficiencies approaching 70 percent have been achieved. The continuing development of solid state items will provide for communications systems where power utilization is an important consideration.

The electron beam devices include the traveling wave tube amplifiers and represent the established technology for high frequency, high power, and long distance transmission. The units have had a continuing development in terms of materials improvements and internal configurations. The present levels of capability produce power levels up to 500 watts at about 50 percent efficiency; higher power levels have been attained. In operation, these units require DC power supplies in the kilovolt range plus the generation of magnetic fields for beam focusing. These requirements present complexities to some space flight applications. The coupled cavity concept may be considered an extension of the traveling wave concept. The most recent development has seen a three-cavity unit produce power levels up to one kilowatt and anticipates development up to the two-kilowatt range. These units do require the same high voltages as the traveling wave tubes and higher magnetic fields for beam containment. For some configurations, the field requirements can only be met with superconducting niobium magnets.

4.8.2.4 Receiver Detectors

The performance of receivers relates to the intrinsic losses that occur in the detector-amplifier combination. Receiver noise establishes the signal level threshold needed for operation. The TDAS has identified receiver noise limit effects in the range 4 to 6 db over the operating frequencies of the system. The detector portion of the noise becomes 1.5 to 3 db and represents about a factor of two improvement over present items. Developments in detectors focus upon the GaAs system generally configured as field-effect transistors. Alternate configurations are under development, particularly for frequencies at 100 GHz or above. Developments also address cooled detectors. Cryo-cooled super conducting tunnel junction systems show performances approaching the fundamental quantum limits.

4.8.2.5 Optical Transmission Systems

Lasers with high speed off-on modulation provide the means for obtaining serial data transmission at gigabit-per-second rates. The laser beam operates with some form of pulse modulation (position, intervals, amplitude, etc.) and utilizes an optical telescope as the signal receiver. The detectors presently available operate in the tens of picosecond range; the combination provides the basis for operating with fraction of gigasecond pulses. The laser-based optical systems impose stringent requirements for precision pointing. Laser beams are narrow; pointing accuracies must achieve one microradian or less with line-of-sight jitter less than 0.2 microradian. The lasers presently identified for such applications are the frequency-doubled, neodymium-yttrium aluminum garnet (Nd-YAG) at 0.532 micrometers (green), GaAs at 0.85 micrometers (red), the Nd-YAG at its lasing frequency 1.06 micrometers (near IR), and CO_2 at 10.6 micrometers (IR). The lasers operating in the visible are receiving the most attention and their receivers would utilize a 40 cm optical telescope focused upon an avalanche diode detector. The principal applications envisioned for laser-based transmission become relay links between satellites in orbit with particular emphasis for solar system probes. None of the wavelengths listed have an assured transmission path through the atmosphere of the Earth.

4.8.3 Recommended System

The system recommendations envision an expansion of the present requirements plus the addition of relay communications from distant sources. The expansion of data transmissions to Earth will face the complexity of a saturated utilization for all of the transmission frequency bands that can operate effectively through the atmosphere (including bands that have significant attenuations). The relay data transmission links will operate at data rates and carrier frequencies not generally compatible with transmissions to the Earth (e.g., absorbed in the atmosphere, obscured by cloud cover, etc.). The envisioned capabilities are summarized as follows.

4.8.3.1 Communication Links

The communication functions identified in **Table 4.8.1-1** will continue to exist; the changes anticipated appear as data rates, numbers of simultaneous links, and the operating frequencies. The two-way Earth communications through a relay satellite will present the greatest complexity. The communications links through a relay satellite need to be reserved for priority transmissions (e.g., a requirement for near real time). The Space Station will have the capability to fill all the relay satellite's inputs at their maximum continuous data rates. For such conditions, the relay satellite would operate with no processing (e.g., the "bent-pipe" mode). All formatting, data compressions, etc., would be performed aboard the Space Station. The present best estimate would be 12 channels minimum operating at 300 Mbps each. The carrier frequency will be atmosphere compatible, such as Ku at 15-17 GHz or Ka at 33-36 GHz, with multiple ground receivers. Support data from processing or experimentation will have a capability for dump transmissions to Earth at ground stations of interest. These dumps would occur at compatible frequencies and data rates during an orbital overfly. All 14 of the specific frequency channels assigned to the United States must be accommodated. Prudence dictates an additional coverage for the principal assigned frequencies used by other nations. The dump transmission system must be reconfigurable during flight in terms of adjusting frequencies, data rates, and transmission codes. The transmission links for platforms, EVA, OTV, and supply-docking support will expand by a factor of five, with frequencies shifted upwards into regimes attenuated or absorbed by the atmosphere of the Earth and will expand above the frequencies presently assigned for other functions (e.g., 105 to 130 GHz and up).

4.8.3.2 Tracking Links

The requirements for tracking links will expand with needs for multi-vehicle tracking for each mode identified. Except for the interrogation link to a global position system, the other tracking links will need to operate at frequencies which do not penetrate the atmosphere of the Earth. The optical links for precision docking and deployment would expand by about an order of magnitude to support on-board spacecraft erection, assembly, and fueling operations.

4.8.3.3 Relay Link Operations

Laser-driven optical transmissions will become the established technique for communications with remote satellites. The Space Station will provide a relay capability particularly for lunar or libration point spacecraft. Practicalities again dictate maximum bit rates from remote spacecraft. The need to commandeer the entire ground transmission capability could relate to a short period of real-time relay operation from such a remote spacecraft. The Space Stations should be prepared to carry a minimum of four high-bit-rate laser links with optical telescope receivers. The system needs to have on-board reconfiguration to support differences between data formats and code systems. As an example, a lunar system may need to use a different laser wavelength or coding technique from that used for an outer planet explorer.

4.8.3.4 On-board Communications

The recording and transmission requirements for audio/video and measurement data will compound in responding to increases in mission roles and crew sizes. The requirements anticipate a hundredfold increase for communication support in responding to a tenfold expansion of the crew complement. Link transmission to Earth will not be available for the major portion of on-board recorded data. Transfers of such data will employ a high density semi-permanent record. The candidate considered would be a form of laser optical disc record-erase technique now under development as the Tera Bit Recording System (Joint DOD-NASA, performed by RCA). Such records would be returned to Earth aboard Shuttle return flights. As an example, the video data associated with the on-board assembly and deployment of a spacecraft will generate a significant library of records with no need for real time transfer to Earth. The written records associated with visual inspections during Earth assembly become video recordings for an on-orbit assembly performed remotely by manipulators. Such data have established needs for retention but not as real-time transmissions to the Earth.

4.9 Data Management Subsystem

4.9.1 State-of-the-Art

The salient features of the Data Management Subsystem (DMS) as presented in the ACD (**Reference 7**) and the IOC (**Reference 6**) include: an optical data transmission network, commonality of both interface and embedded hardware, multiple processors and software packages, large information storage capability, and time and frequency references. The DMS is largely conceptual at this time.

The functions of Space Station control and operation will be inherent in the DMS if the role as described in the ACD is followed--"When functioning in an integrated vehicle environment, the DMS provides the connectivity between subsystems, payloads, crew/operators, and the ground interface to accomplish the end-to-end function of control and monitor, and information exchange."

Figures 4.9.1-1 and **4.9.1-2** from the ACD (**Reference 7**) show an overview of the DMS configuration and function. The specific hardware items as currently envisioned are listed below.

4.9.1.1 Standard Data Processor

The SDP provides a standard processing environment for host application software. There will be a family of compatible SDP's in terms of processing and memory capacity. Each member of the family will be fully upward and/or downward compatible with the other members, thereby providing a robust and economical growth part in the processing architecture. An ADP may be dedicated to a subsystem or may be shared across multiple subsystems, depending on individual processing requirements. The largest of the SDP family will have processing capability in the range of 4 mip's, with up to 32 mb of main memory.

4.9.1.2 Embedded Data Processor (EDP)

The EDP provides a standard processing environment in a card level implementation. The EDP will be incorporated into specialized subsystem

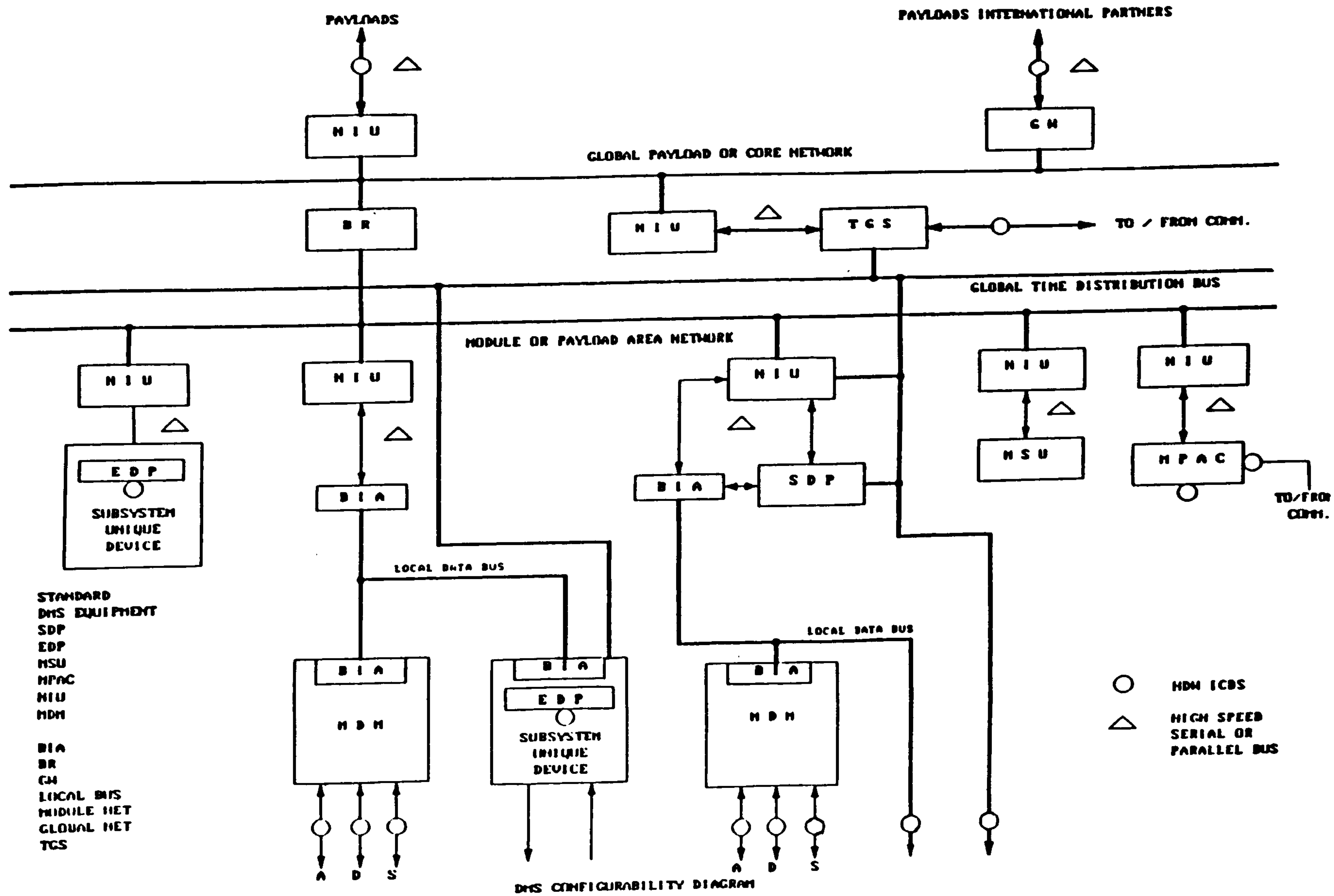


Figure 4.9.1-1 DMS Configuration (Reference 7)

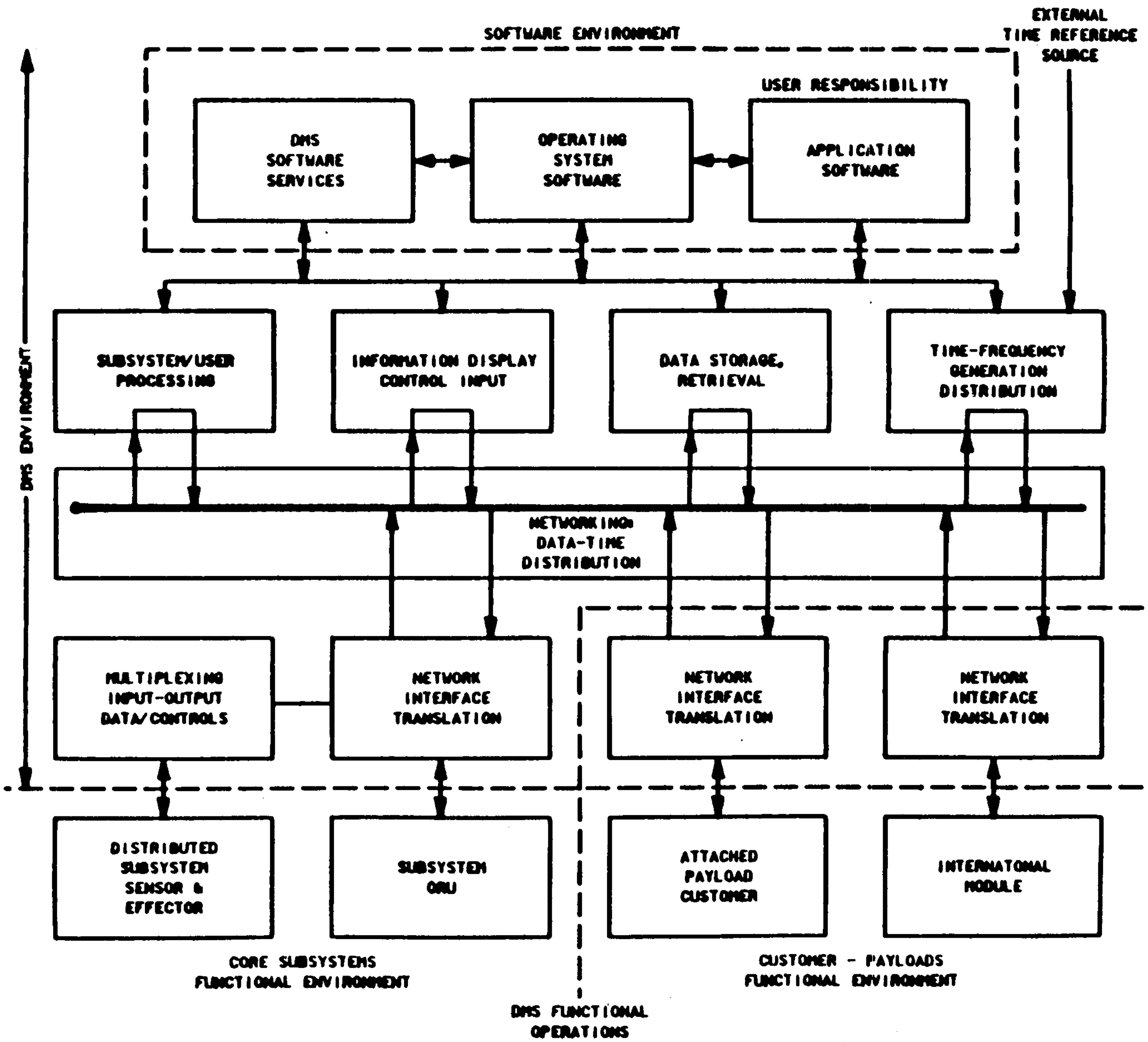


Figure 4.9.1-2 DMS Functional Operations (Reference 7)

elements. It includes an interface to a standard backplane. The EDP also includes an Operating System (OS) that is compatible with that running in the SDP; as a common DMS element, the EDP supports the SSE concept. The EDP does not include direct interfaces to DMS networks or buses; rather, these interfaces would be supplied and configured by the subsystem ORU developer. The EDP has processing capability in the range of 0.5 mips with 1 mb of memory.

4.9.1.3 Mass Storage Unit (MSU)

The MSU is the mass storage unit provided by DMS for core station and payload operations. The MSU has non-volatile memory characteristics. Multiple MSU's are required to meet Space Station on-board storage needs.

4.9.1.4 Multi-Purpose Application Console (MPAC)

The MPAC incorporates display and control devices and provides the operational crew interface to the Space Station core and payload systems. THe MPAC is the electronic core resident within a crew workstation. The workstation also includes the structural support and external configuration of MPAC elements as well as equipment to support crew members in performing tasks. The MPAC will use multifunctional displays and controls. There are three types of MPAC's: fixed, portable, and helmet or head mounted. The MPAC's will have sufficient processing capability and memory to support crew workstation services. They will interface via an NIU to the DMS network.

4.9.1.6 Network Interface Unit (NIU)

The NIU provides access to shared DMS local networks. It contains DMS software but not non-DMS application software. The NIU is packaged in two ways: (1) a full NIU capable of supporting the full range of DMS end-to-end communications services, and (2) a partial NIU capable of providing a subset of data transport services. The partial NIU supports users who require upper layer services, such as file transfer and address or interactive sessions.

4.9.1.7 Multiplexer/De-Multiplexer (MDM)

The MDM operates as a remote I/O device for (1) acquiring, conditioning, multiplexing, and transferring subsystem sensor data to the subsystem data processor; and (2) routing, conditioning, and distributing commands and data from the subsystem data processor to subsystem effectors.

4.9.1.8 Bus Interface Adapter (BIA)

The BIA is a standard DMS-provided unit for connecting DMS and other subsystem equipment to DMS-defined local data buses, implementing the lower layer protocols.

4.9.1.9 Bridge

A network bridge provides access from a DMS local network or a non-DMS local area network to the global station network that runs between modules. It contains DMS software but not non-DMS application software. Since the DMS global and local networks are identical and use the same protocols, the bridge does not need to perform protocol conversion.

4.9.1.10 Gateway

A network gateway provides access from a non-DMS local area network to a DMS local network or to the global station network that runs between modules. It contains DMS software but not non-DMS application software. Since the DMS and non-DMS networks are assumed to be different and implementing different low-level protocols, the gateway has to perform protocol conversion to an agreed-upon standard interface at the data link layer. This gateway is predicated on program-wide agreements on communications protocols at the logical link layer and above; it will greatly increase in cost and complexity if these agreements are not achieved.

4.9.1.11 Local Bus

The DMS shall provide one or two local bus standards as media for data transport between subsystem sensors/effectors and BIA's. The BIA's in turn provide connectivity to SDP's.

4.9.1.12 Local Network

A DMS local network is defined as any core or payload network that is confined within a specific region of the Space Station, for example a module. It is "owned" by the DMS in the sense that the DMS monitors and maintains its health and controls its use through the NOS.

4.9.1.13 Global Network

A global network is defined as the core of payload network that is not confined to a specific region of the Space Station and, in particular, runs between modules. It is "owned" by the DMS in the sense that the DMS monitors and maintains its health and controls its use through the NOS. The DMS global network is a high speed, 100 mbps, standard medium.

4.9.1.14 Time-Generated System

The time and frequency generation system comprises time and frequency sources, comparators, processors, and controllers to generate accurate and stable time and frequency information as required by Space Station systems.

4.9.2 Technology Trends

On-board data processing is one of the most rapidly advancing areas of space systems technology and as such can affect all of the Space Station's subsystems and functions. Future systems will have higher processing rates, will come in smaller packages, and will support networked architecture for on-board signal processing (Reference 2). Reliability and fault tolerance will be required attributes.

Technology forecasts for components of a data management system are given in Reference 2 and are presented herein as Table 4.9.2-1.

4.9.3 Candidate Advanced Subsystem

Because of rapid developments occurring in this area, no specific subsystem components were selected for this study. It appears that such selections may well depend on factors such as reliability, fault tolerance, ease of replacement, and ease of repair.

TABLE 4.9.2-1 ON-BOARD PROCESSING TECHNOLOGY FORECASTS (REFERENCE 2)

Figure of Merit	1985	1990	1995	2000
On-board Processors				
Spaceborne Computers Performance (Mops)	10	40	100	200
Signal Processors Throughput Rate (Mops)	20	100	1,000	—
Microprocessors Performance (Mops)	1	15	30	60
Controller Chip Complexity (gates)	1×10^5	2×10^5	5×10^5	1×10^6
Data Storage Systems				
Magnetic Tape				
Capacity (bits)	4×10^{10}	1×10^{11}	3×10^{11}	1×10^{12}
Transfer Rate (bps)	3×10^7	1×10^8	3×10^8	1×10^9
Bubble Memory				
Capacity (bits)	5×10^7	1×10^9	—	—
Transfer Rate (bps)	$<1 \times 10^6$	4×10^6	—	—
Optical Disk				
Capacity (bits)	*	1×10^{13}	—	—
Transfer Rate (bps)	*	1×10^8	—	—
Artificial Intelligence/Expert Systems				
Knowledge Base Size (rules)	1×10^3	1×10^4	1.5×10^4	2×10^4
Knowledge Base Throughput (rules/sec)	400	4,000	6,000	8,000
Software Productivity				
Productivity Rate (codelines/man-year)	900	2,500	5,200	8,300

*Technology not available

5.0 SUBSYSTEM SYNERGIES FOR SPACE STATION

Space Station synergies represent opportunities for subsystems to beneficially share items of equipment, functions, or configurations that enhance the total operation of the station. The assessment for synergies reviewed each subsystem in conjunction with each of the others to identify potential areas of beneficial interactions. These results are summarized below; the synergy between life support, propulsion, and electrical power has received an estimate of the overall mass balance effects from generating O_2-H_2 as propulsion fuel by electrically decomposing water.

5.1 Assessment of Synergies

The initial evaluation for subsystem synergies identified five opportunities for beneficial interactions. These are summarized in a sequence based upon the number of subsystems involved with a particular synergy.

5.1.1 Life Support, Propulsion, Electrical Power, Guidance/Control, and Experimentation in Relation to the On-board Generation of O_2-H_2 Fuel

The life support system provides the O_2 for reconstitution of the cabin atmosphere by the on-board electrolytic decomposition of water. The H_2 generated reduces CO_2 to elemental carbon and water. The system recovers water from the air and recycles waste water to achieve a net balance that actually shows a small degree of water surplus. The expansion of the electrolysis capability up to the levels required for on-board propulsion as fuels for attitude control, reboost, and auxiliaries together with a more extensive recycling of wastes improves the water recovery balance and provides a means for load leveling in the electrical power system. Fuel generation at the rate of 13,500 kg (30,000 pounds) per month would utilize less than 10 percent of the total power available and offers a substantial opportunity for load leveling by absorbing any excess power. One of the principal microgravity processes demonstrated during Shuttle flights involves the electrophoretic separation of organics in aqueous solutions. The depleted stream from this experiment could pass through the life support oxidizer and provide supplemental feed water for electrolysis. An initial estimate of the life support interactions appears as Section 5.2 below.

5.1.2 Thermal Control, Electric Power, Life Support, and Experimentation As the Integration of Thermal Control Buses and Loops

The thermal control system provides the means for removing or supplying heat at specific locations throughout the Station. The concept envisions a series of loops such that one user's sink is another system's source. Typically, the condensate loop for the power generation system would provide sensible heat for experiments, cabin temperature control, etc. A low temperature bus would extract heat from localized generators such as experiments, electronic or electrical equipment, etc., and operate through an exchanger to a space radiator.

5.1.3 Thermal Control and Structure As the Selection of the Pressure Shell Materials to Provide a Heat Transfer Radiator

The construction of the pressure shells from materials such as graphite fiber in an aluminum matrix can provide a direct thermal path through the wall for radiation. In such an installation, the fluid loops would be on the inside and in contact with the pressure shell; the external radiation heat transfer could be enhanced by a locally applied coating that improved the emissivity. As an alternate, a wound or wrapped pressure shell formed from a tubular member would provide a means to circulate heat transfer fluids locally within the walls of the pressure shell.

5.1.4 Electrical Power and Experiments By the Solar Collectors to Provide a Concentrated Solar Flux for High Temperature Experiments

A Space Station power system based upon solar powered dynamic generators (turbines or reciprocators) has large area solar concentrators focused into high temperature receivers. The receiver and related structure provide a mounting access for research experiments which can benefit from the 6,000 K equivalent heat source.

5.1.5 Attitude Control Using Water Storage as an Inertial Balance in a Rotating Spacecraft

The utilization of rotation to produce an artificial gravity in habitated areas shows benefits for Space Station operation. The elimination of gyroscope effects by counter rotations simplifies attitude control requirements. A counter-rotating member constructed as the water storage tank would provide a means for inertial matching by velocity adjustment as well as providing the needed reservoir for water supplies.

5.2 Operating Synergy from O_2-H_2 On-board Generation by Water Electrolysis

The selection of O_2-H_2 as the general-purpose Space Station propellant and fuel offers beneficial synergies between the life support, propulsion, and electrical power systems. An expansion of the electrolysis capacity to provide fuel for station attitude control, reboost, and the OMV appears to benefit the life support system and electrical power as well as simplifying resupply logistics. The description of the synergies will first summarize the life support system used as the basis for comparison and then proceed to show the effects on water utilization of on-board production of O_2-H_2 in quantities associated with fuel or propellant utilization.

5.2.1 Summary of the Baseline Life Support System (Present IOC)

The presently defined IOC life support system provides the baseline for constructing a comparison; **Figure 5.2.1-1 (Reference 6)** shows the principal features and illustrates the daily mass flows required to support a six-person crew. The pertinent features for later comparisons show that:

1. Electrolysis of water provides the O_2 supply for reconstitution of the cabin atmosphere.
2. The H_2 from electrolysis performs the CO_2 reduction utilizing the Bosch process.
3. Water from condensate and CO_2 reduction provides the potable supply and balances the water O_2-H_2 requirements.
4. The water for electrolysis is drawn from the recycling of water for hygiene which includes the processing and decomposition of urine.

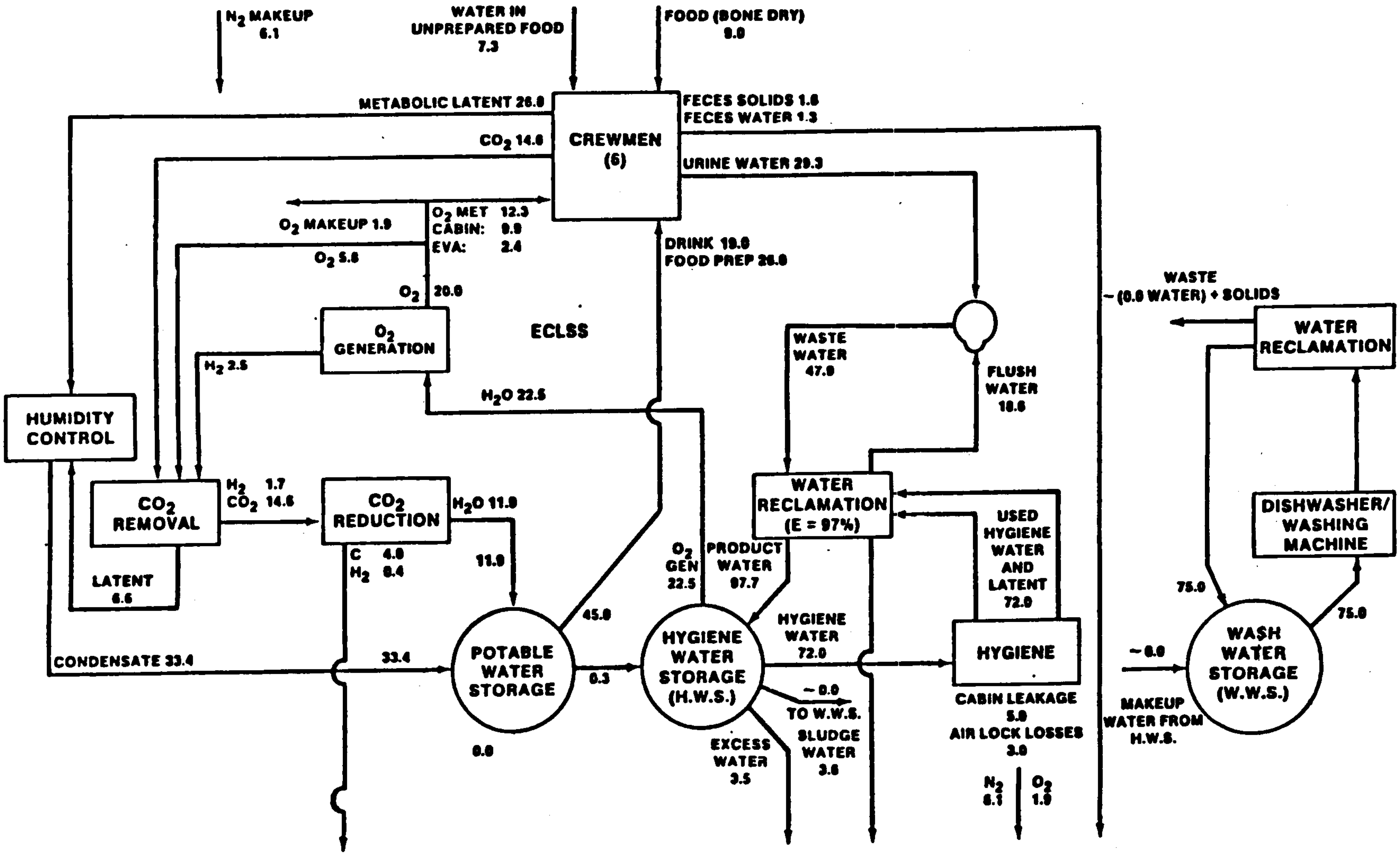


Figure 5.2.1-1 Partially Closed ECLSS Mass Balance (pounds/day) (Reference 6)

5. Wash water has its own independent recycle.

5.2.2. Synergy System Parameters

The system envisioned for synergistic comparisons relates to a new, larger Space Station that has a matured capability to perform all the functions intended. The on-board population has been established at 60 persons. Life support requirements are adjusted upward as follows:

1. The requirements for atmosphere (including leakage) and food together with waste outputs are direct multiples equal to 10 times the values shown in **Figure 5.2.1-1.**
2. The water used for flushing purposes is set at three times the baseline usage and becomes a factor of 30 relative to the baseline.
3. The water requirement for the hygiene loop and the water requirement for wash are doubled to result in a factor of 20 relative to the baseline.

The system as defined envisions a significant increase in the utilization of water, particularly for crew-comfort functions.

5.2.3. Synergized System Description

The system intended for O_2-H_2 combined production supports an on-board crew of 60 individuals and recycles all the water from dish washing, clothes washing, and hygiene-related functions. The system also oxidizes all human wastes. The system flow and mass balance diagram appears as **Figure 5.2.3-1.** The principal features are:

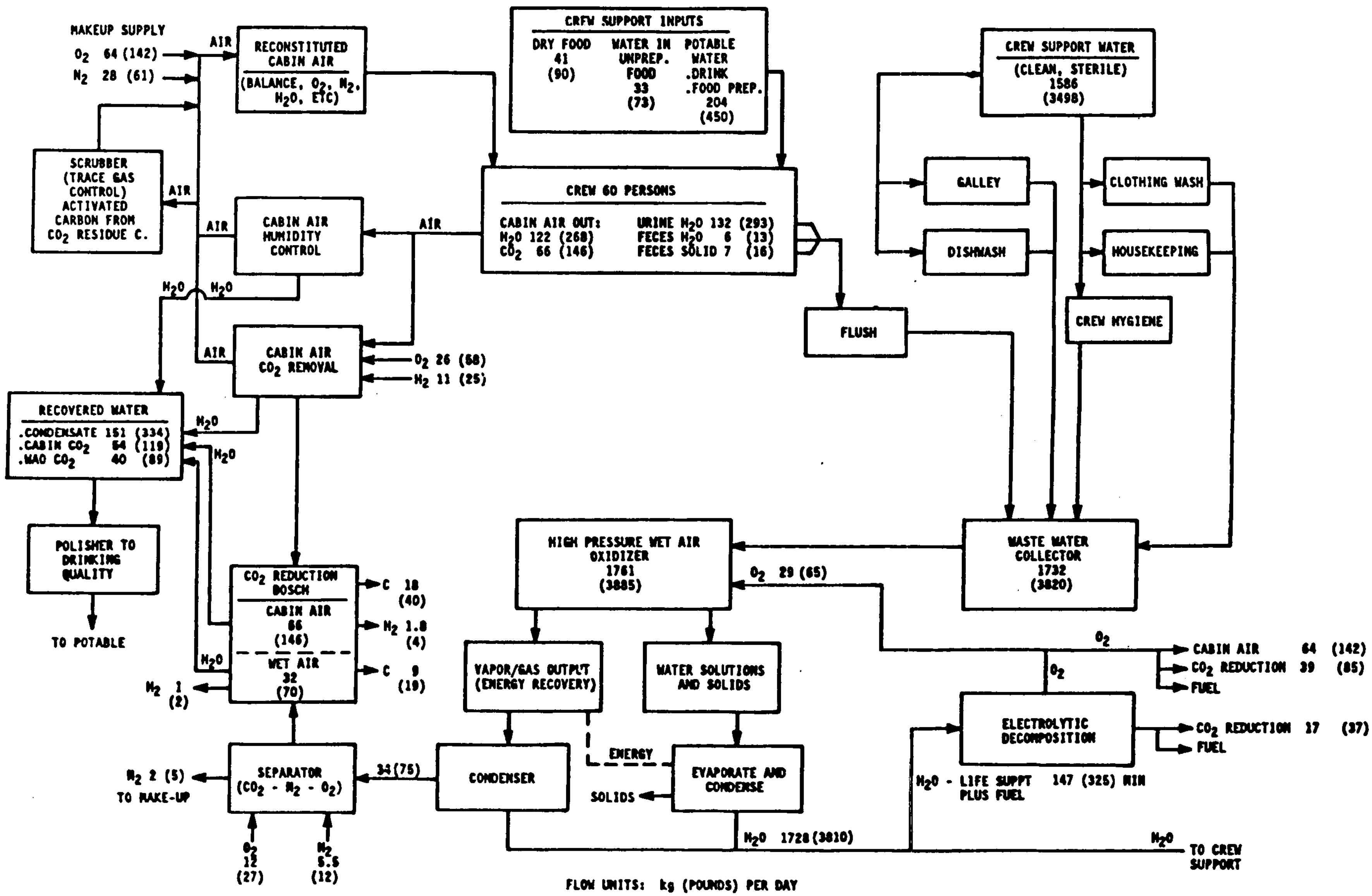


Figure 5.2.3-1 Mass Balance for 60-Person Crew Using Wet Air Oxidation Reclamation and O_2-H_2 Generation

1. Electrolysis of water provides the O_2 for reconstitution of the cabin atmosphere, plus the oxidation of wastes and propellant/fuel requirements.

2. The H_2 from electrolysis performs CO_2 reduction from both cabin air extractions and from the oxidation of carbonaceous wastes.

3. The oxidation of wastes from humans, the galley, laundry, and cleaning employs the wet air oxidation technique operating at temperatures and pressures which provide both sterilization and complete combustion.

4. The dissolved salt effluent (and residual solids) from the wet air oxidizer are precipitated to dry crystals by a distillation system which has the option to include reverse osmosis as one of the extraction steps. The water output of the wet air system eventually provides the input to the electrolytic cells.

The values for mass balance involving wet air oxidation assumed the urine to be 1.5 percent N_2 as urea; waste from hand, clothing, and dish washing was taken as 0.25 percent stearate soap. The oxidizable portion of feces content was set as all carbon. The unoxidizable solids were set at 10 grams per person per day. The auxiliary reduction of CO_2 is considered conservative to provide an upper demand level for the electrolysis capacity.

5.2.4. Rationale for Wet Air Oxidation

The utilization of wet air oxidation for disposal of wastes and accomplishing sterilization is based upon the present level of development for the process together with an apparent potential for providing a general purpose disposer of carbonaceous organics. A summary of the technique and related technology presented in a recent technical journal (**Reference 40**) illustrated the applications of wet air oxidations to the disposal of sludge and similar waste materials. The ability of water to dissolve oxygen at elevated pressure provides a means to initiate exothermic oxidation of otherwise incombustible organics and achieve a net power gain from the process. The utilization of pure oxygen enhances the process. The technology has proven effective in applications to the point where such equipment is manufactured commercially for continued operation at conditions just below the critical point for water (critical point at 21.5 MPa and 375^o C). The continuing evaluations by the LaRC have shown that operation above the critical point improves the oxidation of organics and reduces nitrogen compounds to elemental forms (**Reference 41**). The reactor envisioned for space would utilize a high strength reinforced material such as graphite fiber in an aluminum matrix with the surfaces in contact with the reacting liquids having additional oxidation protection (e.g., Al_2O_3, ZrO_2, chromium). The system would operate in a manner to perform a complete oxidation. For conservatism, the diagram (**Figure 5.2.3-1**) includes the post oxidation steps of evaporation for solids removal while recognizing that precipitation of inorganic solids (such as NaCl) would occur during supercritical operations.

5.2.5 Assessment of System Operation

The pertinent considerations associated with providing O_2-H_2 propellant/fuel in synergy with the life support requirements appear summarized in **Table 5.2.5-1.** The requirements and effects are presented for the cases of 237 kg (500 pounds) and 475 kg (1,000 pounds) O_2-H_2 propellant production each day. The lower rate would supply reboost and attitude control with 4,750 kg (10,000 pounds) per month available for the OTV; the upper rate would provide the additional capacity for a monthly fueling of the equivalent to a Centaur booster.

In reviewing the operation, both rates of production would have to first provide the life support requirement of 147 kg (325 pounds). The total water processing for on-board life support functions is 1,938 kg (4,273 pounds) per day. The reclamation of all water, including extractions from the WAO-produced CO_2, provides a net 36 kg (79 pounds) daily gain in actual water. At an Isp of 440 seconds, this weight of fuel provides more than five times the present impulse requirement for attitude control and reboost. The generation of O_2-H_2 for propulsion or fuel allows the use of unprocessed fresh water for potable usage and reduces the quantity of recycled water needed for life support. At a fuel generation rate of 237 kg (500 pounds), only 13 kg (29 pounds) of recycled condensate needs finishing to the point of potability. For a fuel generation of 475 kg (1,000 pounds) per day, all potable water would be drawn from stores along with about 13 percent of the supplemental needs.

An assessment of the power impact compares the requirement for electrolysis with the total available. An electrolytic cell operating at 70 percent efficiency requires 2.7 kilowatt hours of electric energy to produce a pound of water. For a Space Station which provides 2.5 MWe equivalent continuous power, the electrolysis operation to produce 237 kg (500 pounds) of fuel corresponds to 3.5 percent of the power available; 475 kg (1,000

TABLE 5.2.5-1 ASSESSMENT OF DAILY WATER REQUIREMENTS FOR ON-BOARD GENERATION OF O_2-H_2

Summary of Requirement	Fuel at 237 kg (500 lb./day)	Fuel at 475 kg (1000 lb./day)
A. Electrolysis Requirements		
o Electrolysis for Life Support	147 kg (325 lb.)	147 kg (325 lb.)
o Total Electrolysis Required	386 kg (825 lb.)	601 kg (1325 lb.)
B. Water Needs or Utilization		
o Potable Drinking Quality	204 kg (450 lb.)	204 kg (450 lb.)
o Hygiene and Washing	1586 kg (3498 lb.)	1586 kg (3498 lb.)
o Life Support Electrolysis	147 kg (325 lb.)	147 kg (325 lb.)
o Total Requirement	1938 kg (4273 lb.)	1938 kg (4273 lb.)
C. Water Available from Recycle		
o Cabin Air and Crew CO_2	205 kg (453 lb.)	205 kg (453 lb.)
o CO_2 Reduction from WAO	40.3 kg (89 lb.)	40.3 kg (89 lb.)
o Direct from WAO	1728 kg (3810 lb.)	1728 kg (3810 lb.)
o Total Recycled	1974 kg (4352 lb.)	1974 kg (4352 lb.)
- Additional Water Created by Recycling	36 kg (79 lb.)	36 kg (79 lb.)
- Net Draw to Provide Fuel from On-board Storage Supply	191 kg (421 lb.)	417 kg (921 lb.)

TABLE 5.2.5-1 ASSESSMENT OF DAILY WATER REQUIREMENTS FOR ON-BOARD GENERATION OF O_2-H_2 (Concluded)

Summary of Requirement	Fuel at 237 kg (500 lb./day)	Fuel at 475 kg (1000 lb./day)
D. Water Utilization Sources		
(a) Potable 204 kg (450 lb.)		
o From Supply	191 kg (421 lb.)	204 kg (450 lb.)
o From Condensate	13 kg (29 lb.)	0
(b) Wash and Hygiene 1587 kg (3498 lb.)		
o From Supply	0	213 kg (471 lb.)
o From Recovered Water (Condensate and CO_2)	231 kg (508 lb.)	243 kg (537 lb.)
o From the WAO Output	1356 kg (2990 lb.)	1129 kg (2490 lb.)
E. Electrical Power Requirement (70 percent efficiency)	2220 kWh	3580 kWh

pounds) of fuel equates to 6.7 percent of available power. Both of these loads are within the anticipated cyclic variations in total station power demand. The on-board generation of O_2-H_2 for propellants and the supply for auxiliary fuel cells offers an attractive means toward load leveling of the electric power generation system by operating the electrolytic cells with the excess power available at any time.

6.0 ADVANCED TECHNOLOGY SPACE STATION CONFIGURATION CONCEPT

6.1 Approach

The subsystem candidates of Section 4.0 were selected to provide maximum synergism for an integrated Space Station configuration. In particular, the EPS, ECLSS, thermal, and propulsion subsystems were selected to have an interplay of energy and material use related by a water, hydrogen, and oxygen base to the extent practical. In addition, high-grade heat energy of the EPS is usable directly by the other subsystems without the double conversion from heat to electrical energy and back to heat output wherever transport distances are reasonable. Lower grade heat energy from the EPS heat engine outlet is available for thermal control, which effectively reduces the thermal subsystem loads and reduces EPS radiator requirements. Section 5.1 described the potential synergisms between the selected subsystems on the integrated Space Station.

The integrated Space Station is selected to have portions that provide artificial gravity and portions that are stabilized for Earth and space viewing and for docking and servicing facilities. The rationale for artificial gravity is covered in Section 6.3. In addition to the synergism of subsystems and the requirement for artificial gravity, other factors considered are the power output needed, the crew size to provide the functions listed in Section 2.0, the Space Station orientation relative to Earth and Sun, and the capability for additional growth.

6.2 Estimates of Power Requirements and Crew Size

The seventeen functions identified for the Advanced Technology Space Station received estimates for electrical power consumption and crew requirements. The estimates draw from the source references used throughout the study and include a contingency margin. The estimates of power requirements for each of the functions and the contingency appear in **Table 6.2-1.** For crew estimates, the functions have been grouped into six general categories and summarized as follows:

CATEGORY	NUMBER OF OCCUPANTS
Operation	12
Science	10
Manufacturing	12
Transients	14
Medical	6
Contingency	6
TOTAL	60

6.3 Considerations for Artificial Gravity and Space Station Orientation

The major arguments for artificial gravity on a Space Station are the need for the occupants to avoid physiological problems associated with Coriolis acceleration, motion sickness, general disorientation, bone demineralization, loss of muscle tone, and loss of traction. Some subjects are more prone than others to various aspects of these possible problems.

Table 6.2-1 Estimated Electrical Power Requirements for the Space Station Functions Listed in Section 2.0

Function	Broad Category	Electric Power Requirements, kWe
1) Observation Platform	Science	10
2) In Orbit Science	Science	10
3) Service and Repair	Operations	5
4) Manufacturing & Assembly	Manufacturing	500
5) Transportation Node	Operations	10
6) Crew Habitat	Habitation	5
7) Communications Center	Operations	50
8) Adaptation Area	Habitation	5
9) Storage Node	Operations	10
10) Variable "g" Facility	Science	5
11) Commercial Manufacturing	Manufacturing	1,000
12) Energy Collection & Relay Station	Operations	25
13) Medical Facility	Medical	20
14) Tourism (Transients)	Habitation	10
15) Horticultural Research	Science	10
16) Technology Demonstration Facility	Science	50
17) Control Center for Satellites	Operations	-
TOTAL ELECTRICAL POWER REQUIREMENT		1.725 MW
TOTAL ELECTRICAL POWER OUTPUT		2.5 MW

References 22, 36, and 42 provide some background on effects of simulated and actual gravity on various subjects. Although the minimum acceptable "g" level and possible relation to exposure time is not defined (and is probably dependent on the individual, training, etc.), some guidance is provided by **Figure 6.3-1** from **Reference 43**.

Another argument for providing artificial gravity is the fact that some physical processes, such as that of an ECLSS, work much better in a gravity environment.

It appears, therefore, that if crew members are to remain in orbit for extended periods of time, provisions should be made for some level of artificial gravity. This could be accomplished by using a rotating section of the spacecraft and using that section as the usual human habitat or for periodic reconditioning as required.

It was decided that the Space Station should have a sun-oriented element on which to mount solar collectors.

6.4 Sizing the Space Station

Figure 6.3-1 was used as a guide in selecting the size and rate of rotation of the turning section of the Space Station. In order to fall within the acceptable operating range shown in the figure while maintaining a reasonable size (diameter) and rotation rate, a gravity level of 5.37 feet per second per second was selected with a module or multi-module rotation **arm of 114.5 meters (375 feet)**. This combination resulted in a rotation rate of 1.14 rpm. The "g" level selected is one lunar "g" and could be used to acclimate personnel for lunar base operation.

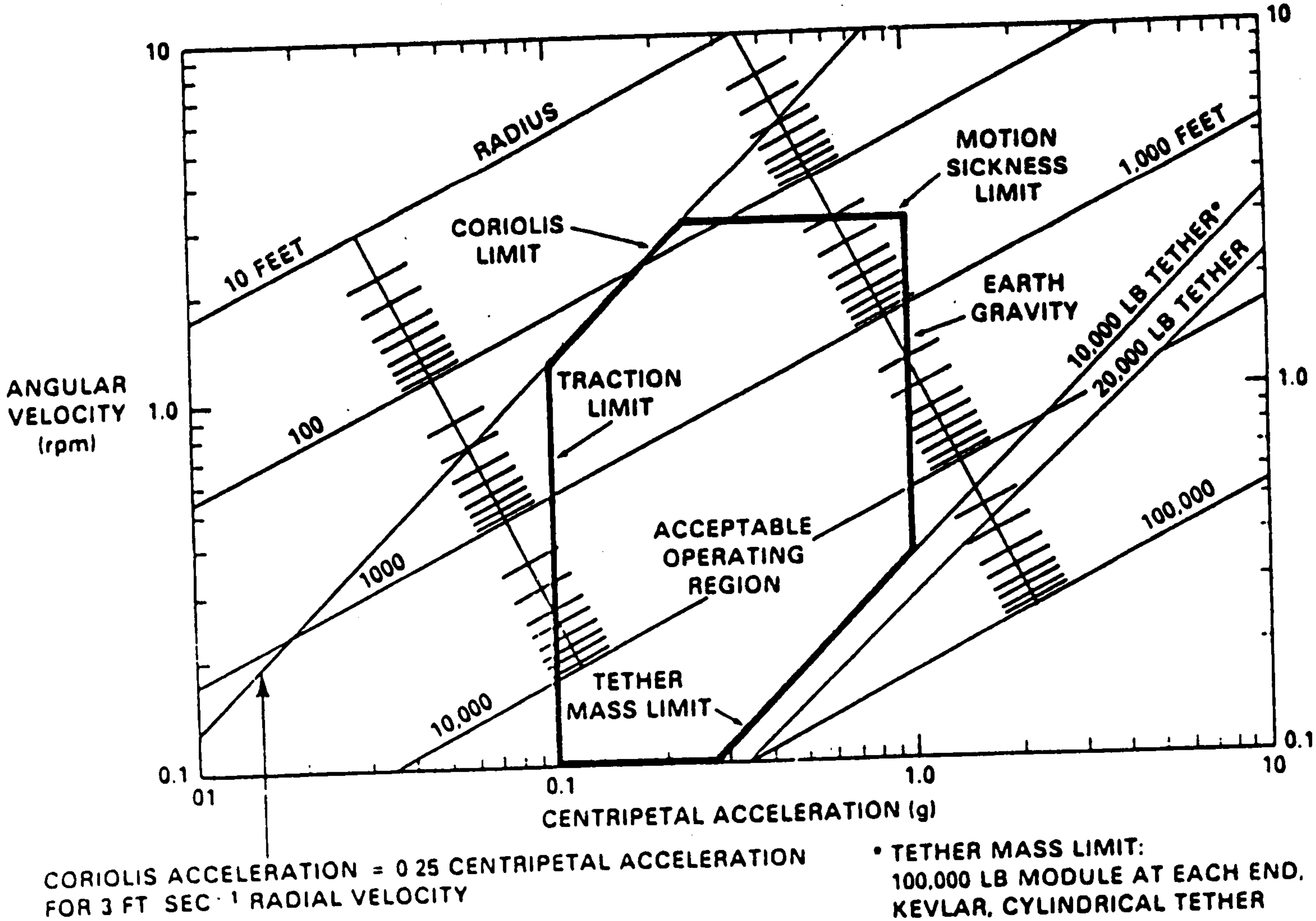


Figure 6.3-1 Artificial Gravity Parameters (Reference 43)

The selected diameter provides adequate area for solar collectors, radiators, hangers, and other Space Station adjuncts.

6.5 Space Station Configuration

The configuration selected, based on the considerations of the previous sections, is shown in **Figures 6.5-1 and 6.5-2**. The large rotating torus could as well be several modules on spokes or a regular polygon made up of many cylindrical sections. Pertinent physical dimensions of the configuration are given in **Table 6.5-1**.

The Space Station features a large cylindrical central tube and a truss platform to which all other sections are attached. The box-like structure at the bottom is the repair, docking, and assembly area. The long cross arm is rigidly attached to the central tube and is used for mounting Earth-pointing devices. Four solar collectors are attached to the sun-oriented platform and are the prime power source for any equipment in the cross arm. Two solar collectors are attached to the rotating torus and are the primary energy source for equipment in the torus.

The two disc-shaped structures, one on each side of the torus, are used to reduce the net angular momentum of the Space Station about its axis to zero. One of the disks rotates in the opposite direction to that of the large torus. The second disk is fixed relative to the center core; however, its contents (probably water) will rotate opposite to the torus. The rate of rotation can be varied by using pumps. This could be used to trim out the angular momentum. The axis of rotation of the torus is parallel to the plane of the ecliptic and continuously points toward the sun. Therefore, the Station must precess continuously at the rate of one revolution per

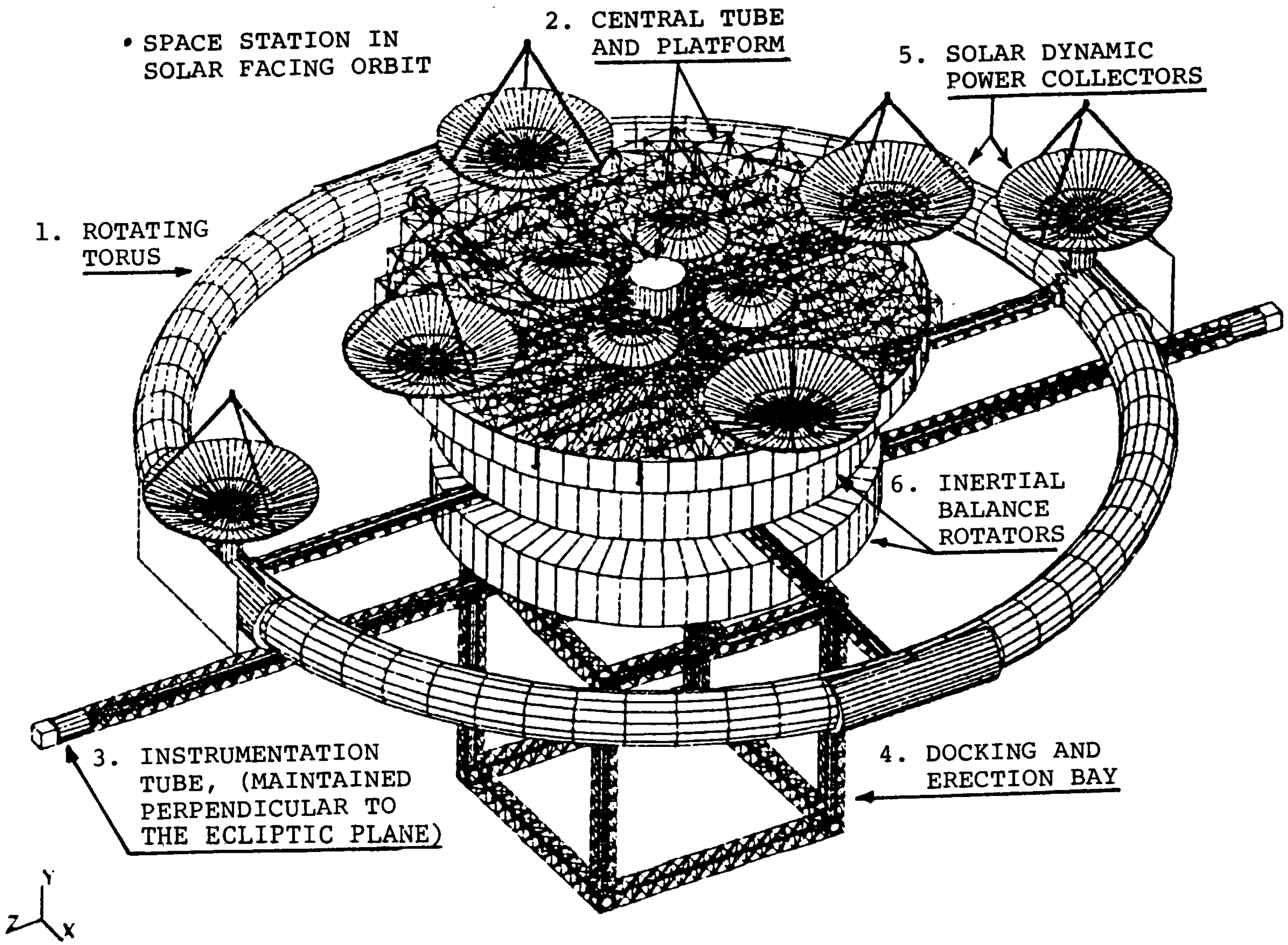


Figure 6.5-1 Advanced Technology Space Station Concept, Features as Described in Table 6.5-1, Solar Facing Side

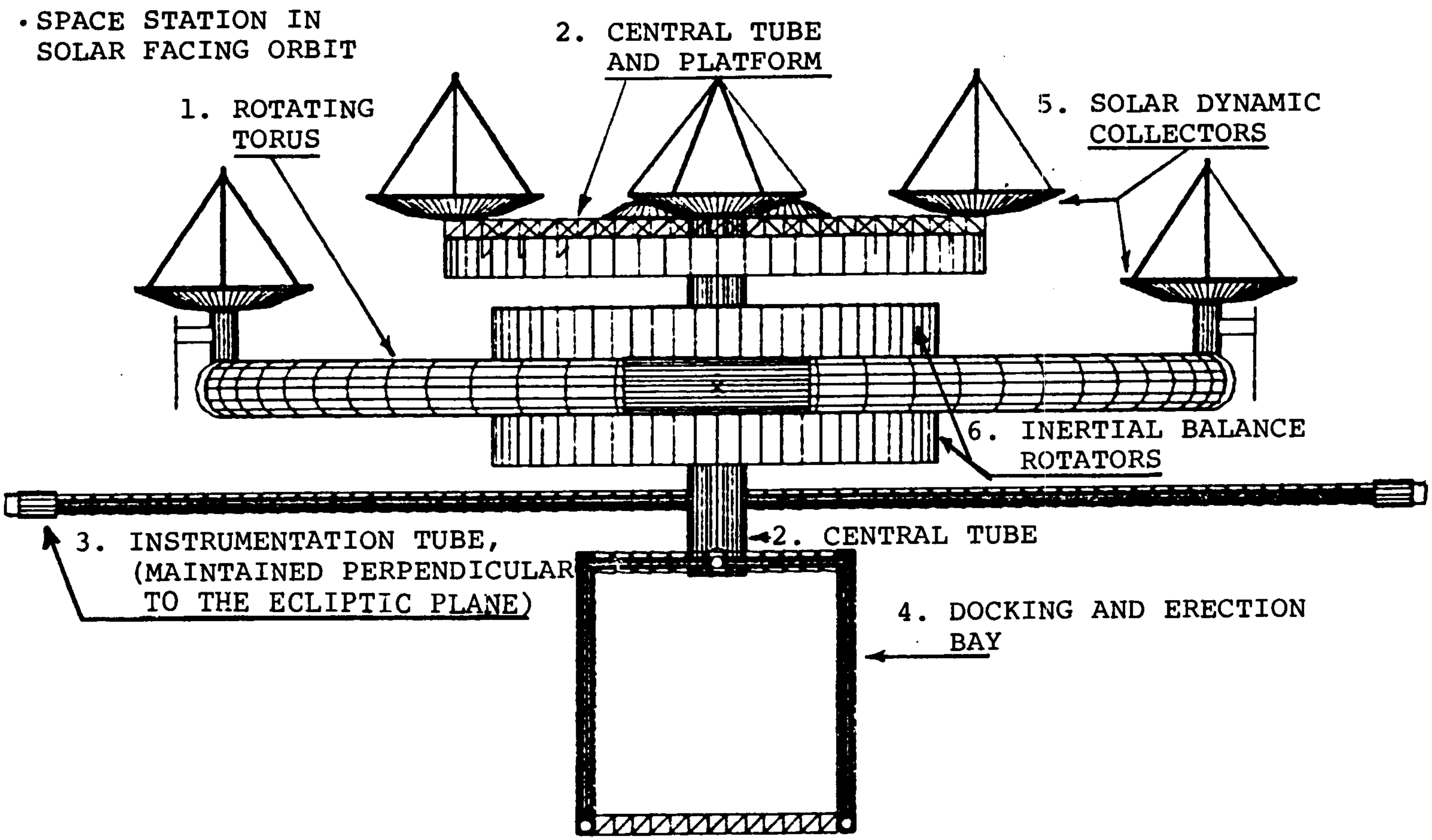


Figure 6.5-2 Advanced Technology Space Station Concept, Features as Described in Table 6.5-1, Side View

TABLE 6.5-1 ADVANCED TECHNOLOGY SPACE STATION, SUMMARY OF PERTINENT FEATURES

A. PRINCIPAL ELEMENTS AND FUNCTIONS

Element	Function
1. Rotating Torus	Habitat and medical, life support and fuel generation, communication and control center, variable gravity facility, component fabrication, storage
2. Central Tube & Platform	Structural core, materials transfer, microgravity processing, solar observatory and horticulture research, orbital science and technology, air lock, storage
3. Observation Tube	Earth and space instruments, communications antennas, energy relay beams, storage
4. Docking & Erection Bay	Rendezvous and docking for supply, assemble fuel and deploy spacecraft, pressure parts for crew transfer, holding facility for OMV, OTV
5. Solar Dynamic Power Collectors	On-board power generation by 6 units; 4 units on the platform and 2 units on the rotating torus
6. Inertial Balance Rotators	Angular momentum of the torus nulled by counter rotation, on-board water storage

B. ROTATING TORUS, DESCRIPTION AND FEATURES

1. Torus Diameter to Ring	229 m	750 ft.
2. Ring Diameter	15.3 m	50 ft.
3. Spokes as a triangular Truss around a tube diameter	5.6 m 3.2 m	18.3 ft. 10.5 ft.
4. Ring Volume	1.305×10^5 m^3	4.61×10^6 ft.^{3}

TABLE 6.5-1 ADVANCED TECHNOLOGY SPACE STATION, SUMMARY OF PERTINENT FEATURES (Continued)

5. Ring Weight, Total as sum of;		1.65×10^6 kg	3.64×10^6 lbs.
Walls as 0.375" Graphite-Al		8.15×10^5 kg	1.80×10^6 lbs.
Floor Load 30psf, 50% Vol.		8.02×10^5 kg	1.77×10^6 lbs.
O_2,H_2 at atmospheric pressure, 50% of Ring Vol.		3.00×10^4 kg	7.24×10^4 lbs.
6. Moment of Inertia		2.16×10^{10} kgm^2	1.59×10^{10} lbmft^2
7. Angular Momentum for 1.141rpm Provides 0.166g in Ring		2.58×10^9 kgm^2/sec	1.90×10^9 lbmft^2/sec
C. CENTRAL TUBE AND PLATFORM, DIMENSIONS AND FEATURES			
1. Platform, as a Truss:	Bays	5 m	16.4 ft.
	Dia.	158 m	520 ft.
2. Horticulture Domes as Spherical Caps	Dia.	25 m	82 ft.
	High	5 m	16.4 ft.
3. Central Tube Diameter		15 m	49 ft.
4. Central Tube Length		100 m	329 ft.
5. Total Volume		1.762×10^4 m^3	6.24×10^5 ft^3
6. Microgravity Processing Facility as a Levitated Cylinder 8m dia, 25m long		1,260 m^3	4.45×10^4 ft^3
7. Solar Observatory Volume, 15m dia, 10m long		1,762 m^3	6.24×10^4 ft^3
8. Air Locks as Concentric Doors	Full dia -	13 m	42.5 ft.
	Half dia -	7 m	23 ft.
	Small dia -	3 m	9 ft.
D. OBSERVATION TUBE, DIMENSIONS AND FEATURES			
1. Length		290 m	950 ft.
2. Structure as a Square Truss around Tube of Diameter		5 m	16.4 ft.
		3.2 m	10.5 ft.
3. Volume of the Tube		2,210 m^3	7,810 ft.^{3}

TABLE 6.5-1 ADVANCED TECHNOLOGY SPACE STATION, SUMMARY OF PERTINENT FEATURES (Continued)

E. DOCKING AND ERECTION BAY, DIMENSIONS AND FEATURES		
1. The Bay is a Cube	67 m	220 ft.
2. Structure as Square Truss around Tubes of Diameter	5 m 3.2 m	16.4 ft. 10.5 ft.
3. Pressure Ports for Docking that Includes Crew Transfers	One at each of the bottom corners of the bay	
4. Manipulators, 10 Minimum Coverage Internal to Bay Coverage External to Bay (All Faces) All Maniuplators Have the Capability for Interchanging End Effectors	2 minimum at every point 2 minimum at any point up to 15 m (49 ft.), 1 minimum out to 30 m (100 ft.)	
F. SOLAR DYNAMIC POWER GENERATION AS 6 UNITS OF 425 KWE EACH		
1. Collector Diameters (Overall Energy Conversion 0.4)	39 m	126 ft.
2. Radiator Area Total (Equal to Collector Area)	6,950 m^2 (Divides between torus and platform)	74,846 $ft.^2$
3. Mounting & Application, 4 Units on Platform	Power for solar observatory microgravity processing, Earth/space experiments, communications, erections	
Units on Torus	Power for life support, fuel generation, control systems, data systems, on-board fabrications	

TABLE 6.5-1 ADVANCED TECHNOLOGY SPACE STATION, SUMMARY OF PERTINENT FEATURES (Concluded)

G. INERTIAL BALANCE BY A WATER RESERVOIR COUNTER ROTATING AT 10 RPM		
1. Reservoir Dimensions O.D.	92.4 m	300 ft.
I.D.	30.4 m	100 ft.
Thickness	15 m	49 ft.
2. Inertial Balance Estimate		
Moment of Inertia Required	2.47×10^9 kgm^2	1.82×10^9 lbmft^2
Weight of Water Required	1.30×10^6 kg	2.90×10^6 lbs
Water Depth at Reservoir Rim	0.3 m	1 ft
3. Options for Final Trim to Null Balance: Vary the Rotational Speed of the Reservoir, Vary the Water Level in the Reservoir, Provide an Auxiliary Water Channel and Control the Flow Velocity		

year. It will take less energy to accomplish this if the net angular momentum about the torus spin axis is zero.

In the subject configuration, the spokes of the torus and the large cross arm are pressurized to provide a shirtsleeve environment. The cross arm can be used as a repair facility for OMV's, OTV's, etc.

7.0 SUGGESTED TOPICS FOR FUTURE RESEARCH

The present study has addressed the topics assigned by contract. It is broad enough that the writers were required to review a considerable amount of literature and to become more familiar with the Space Station and its subsystems. As is usually the case, the study raised some questions and suggested additional areas of research. These areas are as follows:

1. Continue to explore areas of synergism between subsystems.
2. Explore effects of artificial "g" on subsystems, subjects, materials transfer, manufacturing processes.
3. Make sketches of the Space Station interior to see where functions occur (Geodraw). Estimate weights and inertias of Space Station and its elements. Determine CG locations.
4. Study rotational dynamics, estimating perturbations due to docking, control inputs, and on-board materials movement.
5. Extend point design of EPS to include effects of radiation losses from the heat engine receivers as a function of inlet temperature and variation of system operating temperature range as a function of Carnot efficiency.
6. Evaluate the manufacture of structural elements and pressure vessels in space, including inflatable structures for inflating and hardening in space.
7. Study robotics applications for fabrication, assembly, and deployment.
8. Examine applications of free flying and tethered platforms.

9. Provide inputs to SAB for IDEAS programs to examine Space Station drift, reboost requirements, thermal analysis, and structural analysis.

10. Investigate Space Station surface electrostatic charging and protective measures for damage protection.

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APPENDIX

SOME FACTORS TO CONSIDER IN SELECTING MATERIALS FOR SPACE STATION APPLICATION

Some factors are not relevant to the geometric configuration of a Space Station but must be considered in the selection of materials or components of the Station. These are reviewed briefly.

Coatings

Thermal control coatings are currently in use to successfully control spacecraft temperatures in space. Long-term exposure of the coatings to the space environment and possible contaminants (such as propellant exhaust) require the evaluation of the coating's degradation over an increased lifetime for the advanced Space Station.

Coatings that are electrically conductive with low resistivity and long life are required to suppress Space Station charging (**Reference** 3).

Lubricants and Bearings

The development of improved bearings and lubricants having long life in a space environment is essential for low maintenance of rotating or sliding elements of the Space Station. Proposed solid film lubricants applied by advanced methods have a projected lifetime of 20 years. The need for liquid lubricants possessing self-restoring characteristics will drive the development of highly stable, low vapor pressure, non-contaminating liquids for space applications. Lubricant wearout rather than metal bearing fatigue is the life limiting component of bearing assemblies; therefore, lubricant replenishment is one approach to extending a bearing's useful life.

Bearing modeling using computer analysis and design capability is required to aid in the selection of bearing materials, design features, and lubricant selection and to predict long-term lubricant and bearing performance (**Reference** 3).

Superconducting Materials

Niobium titanium (NbTi) alloys are state-of-the-art superconductors for operating temperatures below 10 K for steady state magnets with current densities of 1-2 x 10^4 amps/cm^2 at magnetic fields up to 8 tesla. Applications that require fast changing magnetic fields will cause a temperature rise in the superconducting composite and loss of superconductance with a temperature rise of one to several degrees Kelvin. Niobium tin (Nb_3Sn) is a brittle intermetallic which shows promise as a fast pulsed and/or high current density superconductor operating at temperatures up to 18.5 K. The manufacture of Nb_3Sn poses enormous problems to achieve the required thermal-electromagnetic stability of the alloy. Reliable manufacturing methods appear feasible by 1990 based on extensive manufacturing, processing, and metallurgical investigations performed to date.

Dielectric insulation materials are in development for providing very high thermally conductive electrical insulation for superconducting wire and embedment of wire turns in superconducting devices. These insulation materials will improve the thermal performance by limiting the temperature rise of devices subjected to large loss terms of the superconductor due to changing magnetic fields (**Reference** 3).

Optical Materials

Materials for fabrication of first surface mirrors and telescope structures are listed in **Tables A-1, A-2, and A-3**. The specific stiffness of each structural material is one of the key parameters of determining the

TABLE A-1 MIRRORS FOR SPACE OPTICS (REFERENCE 3)

Glasses	Type	Optical Utility	Comments
Pyrex	Boro-silicate	Poor	Castable; plentiful supply
Cer-Vit	Boro-silicate	Good	No longer made; stockpile gone
Fused SiO_2	SiO_2	Good	High purity; frit bondable; CTE good at cryogenic temperatures
ULE	Ti silicate	Very Good	Frit bondable; weldable; 0 CTE at room temperature
Zerodur	Glass-ceramic	Very Good	Ultra-low CTE; machinable; not weldable; German source
Heraues	Fused quartz	Very Good	From natural quartz; ultra-pure; good CTE for cryogenic temperatures; German source

TABLE A-2 MIRRORS AND SUBSTRUCTURES (REFERENCE 3)

Material	Application	Comments
Beryllium	Faceplate Substructure Mirror	Requires Ni coating to reduce scatter Unproven for high quality applications Difficult (expensive) to process
Aluminum	Mirror	Very high purity required Good specific modulus Possible CTE problems
Graphite/ Epoxy	Backing structures Metering trusses	Not for optical surfaces Dimensional instability with water absorption-desorption Outgassing potential
Carbon-Carbon	Faceplate Substructure (70 cm mirror)	Good thermal conductivity and dimensional stability Acceptable CTE
Graphite/ Glass	Substructure	Excellent fracture resistance; toughness Acceptable CTE
Graphite/ Magnesium	Faceplate Substrurture	Low angle cross-ply gives needed dimensional stability; low CTE Very good thermal distortion resistance No outgassing

TABLE A-3. PHYSICAL PROPERTIES OF MIRROR SUBSTRATE MATERIALS AT ROOM TEMPERATURE (REFERENCE 3)

MATERIAL	ρ DENSITY gm/cm^3	E MODULUS OF ELASTICITY $10^6 N/cm^2$	k THERMAL CONDUCTIVITY Cal/cm-sec-°C	c SPECIFIC HEAT Cal/gm °C	α COEFFICIENT OF EXPANSION $10^{-6}/°C$
FUSED SILICA	2.20	7.0	0.0033	0.168	0.33
ULE FUSED SILICA	2.21	6.74	0.0031	0.183	0.03
CER-VIT	2.3	9.23	0.004	0.217	0.1
ALUMINUM	2.70	6.9	0.33	0.215	23.9
BERYLLIUM	1.82	28.0	0.38	0.45	12.4

MATERIAL	E/ρ 10^6 cm	$k/\alpha\rho \times 10^3$	$D = k/\rho c$	$\alpha/D \times 10^{-6}$	MICRO-YIELD STRENGTH psi
FUSED SILICA	3.18	2.7	0.008	69	1500
ULE FUSED SILICA	3.05	47.0	0.008	4	1500
CER-VIT	3.7	16.0	0.008	14	1500
ALUMINUM	2.56	8.2	0.92	26	2-8000
BERYLLIUM	15.6	16.5	0.46	27	2-10000

THE MOST SIGNIFICANT PARAMETERS ARE:

(α) = THERMAL EXPANSION COEFFICIENT
($D = k/\rho c$) = THERMAL DIFFUSIVITY
(α/D) = THERMAL DISTORTION INDEX
(ρ) = DENSITY
(E/ρ) = MODULUS-TO-DENSITY RATIO
(Mys) = MICROYIELD STRENGTH

frequencies of fundamental vibrational modes of structures fabricated from each material (**Reference 3**).

Materials for Propellant Systems

A major thrust for liquid propellant systems is to reduce the weight of tanks, pumps, and plumbing. Composite materials and high strength metals made by rapid solidification rate technology or superplastic forming processes are being used in a variety of systems. Carbon-carbon turbine rotors, combustors, and engine afterburner flaps are being developed for the cruise missile and aircraft turbine engines. These advanced materials applications may provide technology spin-off for the advanced Space Station.

Long-life monopropellant space thrusters can be manufactured using a hydrazine-compatible AFE ethylene propylene rubber for valve seats, seals, and expulsion devices and have become universally accepted for hydrazine monopropellant applications. An equivalent elastomer is required for long-life applications of bi-propellant systems to serve in expulsion applications of the oxidizer nitrogen tetroxide (N_2O_4). Manufacturing processes and demonstration of elastomer long-life compatibility with N_2O_4 remains to be established (**Reference 3**).

Materials for Solar Cells

Silicon is the primary solar cell material in use today with a beginning of life efficiency of 15 percent. End-of-life efficiency is considerably lower because of space radiation effects; therefore, solar array design and subsystem efficiency must be sized on the end-of-life efficiency.

Gallium arsenide (GaAs) may emerge as the next generation solar cell material having a beginning of life efficiency of 15 percent. This beginning efficiency is expected to increase with material development. GaAs has a high resistance to space radiation and can perform at a higher temperature than silicon solar cells. Two promising concepts for use of the GaAs solar cells are the flux concentrator and multiple bandgap arrays. The flux concentrator will permit a reduction in size and weight of collector panels and operate at higher efficiency than standard panels. Multiple bandgap arrays will use existing technology to achieve higher conversion efficiency by expanding the frequency bands at which light is absorbed (Reference 3).

Materials for Cryogenic Applications

Space Station storage of propulsion fuels and other fluids at cryogenic temperatures requires materials that can function below 120 K without degradation, cracking, or embrittlement. Cryogenic tankage problem areas are primarily in conduction and radiation heat leakage paths through the thermal insulation and structural supports. A secondary problem results from thermal paths through fittings, ports, and attachments.

Fiberglass reinforced epoxy resin composites are presently used for most cryogenic piping applications, but improvements in the matrix resin's resistance to embrittlement and notch sensitivity are required to preclude leakage and evaporation.

Mechanical refrigerators require low friction and non-wearing materials for long-service life. There is a need for matched expansion seals, which permit the least pressure differential across the seals with extended life capabilities.

The regenerators of mechanical refrigerators require materials with a higher specific heat in the 4-12 K range than lead that is currently used.

Ceramics and metals that undergo magnetic phase transformations at very low temperatures are being developed for this application.

Various felts and screens are used to transfer cryogenic fluids in the zero "g" space environment. Improving and controlling the surface fluid wetting characteristics of the felt or screens could increase the flow rate of the fluid.

Low emissivity, durable coatings and coatings with variable or controllable thermal conductance properties are being sought for use with thermal switches (**Reference** 3).

Contamination

The advanced Space Station will be assembled and serviced in space by transporting structural elements, modules, subsystem components, and resupply items from Earth to low Earth orbit by way of the available space transportation systems. Unmanned cargo vehicles and new manned vehicles will transport cargo from ground station to LEO. An orbital maneuvering vehicle would transfer cargo from the unmanned cargo vehicle to the Space Station. An orbital transfer vehicle would transfer people and cargo from the Space Station to geosynchronous equatorial orbit and to other cislunar orbital positions.

The functionality and mission effectiveness of various Space Station subsystems may be impaired if contamination of telescope mirrors, infrared detectors, and solar cell arrays (as examples) should result during prelaunch, at launch site, ascent, on-orbit, or other space environments. Surface contamination can occur due to particulate, liquid, or vapors deposited during the cargo transit environment or from materials outgassing from the subsystem itself in space.

Possible sources of contamination for the Space Station subsystem or associated spacecraft are identified in **Figure A-1.**

Structural materials should not degrade in a space environment to yield contaminants. Ideally they should be precleanable prior to launch and not degrade by outgassing, moisture desorption, ultraviolet exposure, electrons, protons, micrometeoroid impacts, or atomic oxygen when in orbit.

A comprehensive contamination control program must be implemented from subsystem design through end use to be totally effective (**Reference 3**).

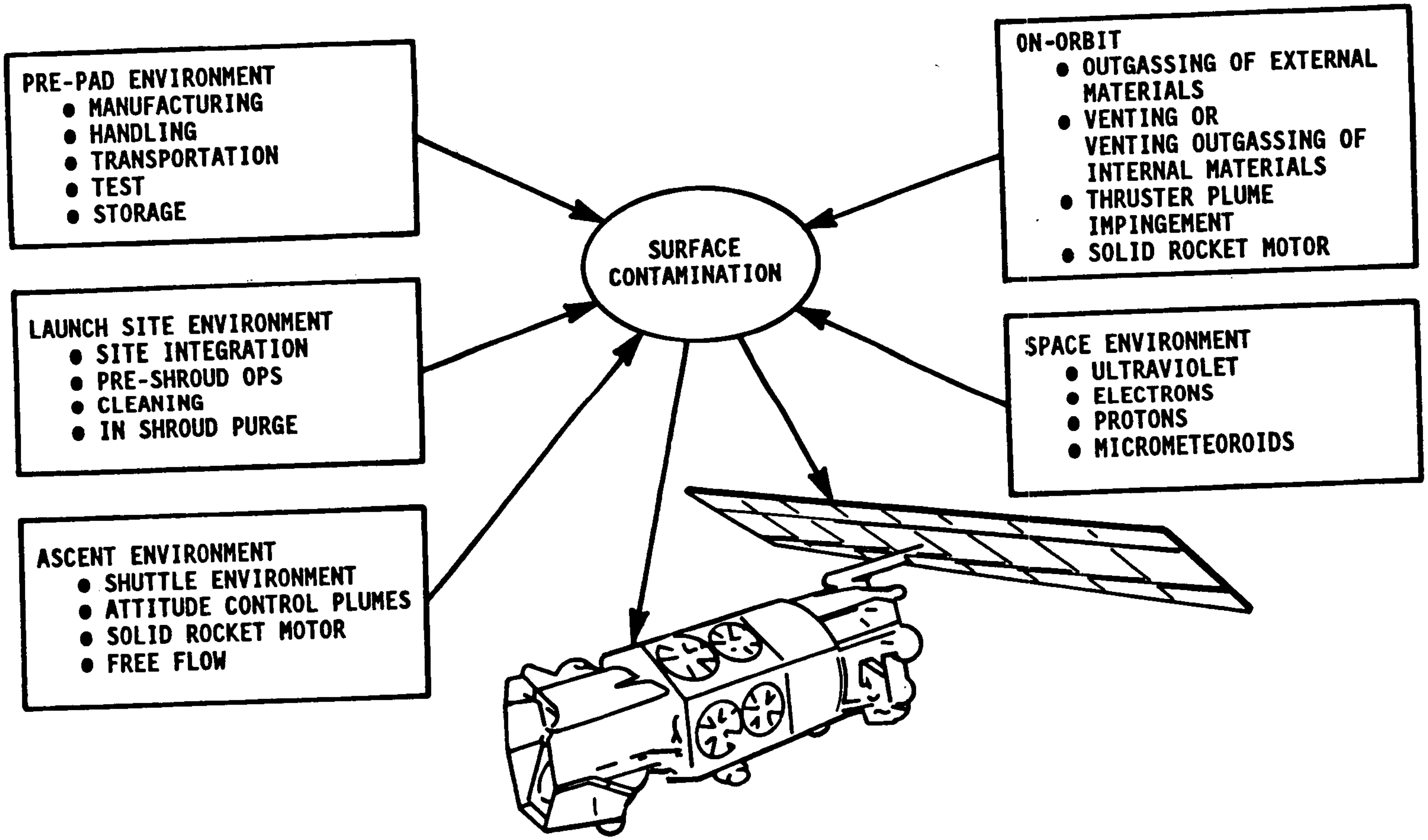

Figure A-1 Sources of Spacecraft Contamination (Reference 3)

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-178208		
4. Title and Subtitle An Advanced Technology Space Station for the Year 2025, Study and Concepts		5. Report Date March 1987
		6. Performing Organization Code
7. Author(s) M. J. Queijo, A. J. Butterfield, W. F. Cuddihy, C. B. King and P. A. Garn		8. Performing Organization Report No.
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9. Performing Organization Name and Address The Bionetics Corporation 20 Research Drive Hampton, Virginia 23666		11. Contract or Grant No. NAS1-18267
		13. Type of Report and Period Covered Contractor Report May, Nov. 1986
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546		14. Sponsoring Agency Code 506-49-31-01
15. Supplementary Notes Langley Technical Monitor - Melvin J. Ferebee, Jr.		

16. Abstract

A survey has been made of potential Space Station missions that might exist in the 2020-2030 time period. Also, a brief study of the current state-of-the-art of the major subsystems was undertaken, and trends in technologies that could impact the subsystems were reviewed. The results of the survey and study were then used to arrive at a conceptual design of a Space Station for the year 2025. Factors addressed in the conceptual design included requirements for artificial gravity, synergies between subsystems, and the use of robotics. Suggestions are made relative to more in-depth studies concerning the conceptual design and alternative configurations.

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